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A Study of Kanban Based Production System in Cellular Manufacturing Environment

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A STUDY OF KANBAN BASED PRODUCTION SYSTEM IN CELLULAR MANUFACTURING ENVIRONMENT

by

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The study of effects of production data variabilities on Kanban based cellular manufacturing system is vital before its design and implementation because it would give better understanding of their uncertain behavior.

In this research, a detailed analysis of a Kanban system, with subcell scenario, under dynamic operating conditions is performed. The Control variables considered were number of Kanbans, processing time variability, demand variability and machine breakdown. The performance parameters considered were profit, production lead time, machine utilization and material processing lead time.

Approximately 200 simulation runs were made with 3 replications each by varying one control variable at a time. The conclusions of this study were that an increase in the number of Kanbans has positive effect on the system performance, only, up to a certain threshold number of Kanbans; processing time variability and demand variability have deteriorating effect on the system performance; effect of demand variability depends upon the number of Kanbans; and machine breakdown in main-line has severe negative effect on the system compared to that of in the subcell. This presented can be used as an effective base for the design of a new system or updating an existing one.

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CHAPTER I

INTRODUCTION

Outline of JIT/Kanban Concept

The Just-In-Time (JIT) principles have gained enormous impetus in several western industries. The main reasons for this are: (a) the perpetual increase in foreign competition, (b) the need to cut down the finished goods inventory, (c) the need to keep up with fluctuations in demand and technological innovations, (d) the need to improve the quality and reliability of the final products and (e) to increase production flexibility (Harmon, 1982).

Japanese firms, especially Toyota, were the first ones to thoroughly demonstrate the power of JIT/Kanban, this is necessary partly because of their own specific situation. Lack of space, coupled with the high costs of importing raw materials, resulted in a need to keep inventory levels and costs at a minimum (Philipoom, 1987). JIT philosophy was specifically developed to fit the unique Japanese culture and work ethic. Japanese customs of lifetime employment, higher education, and homogeneous lifestyles are some unique cultural features which are, to some extent, responsible for the success of JIT philosophy in Japan. Japanese workers tend to be cross-trained, highly skilled and very disciplined, which when combined with a high degree of job automation, results in relatively standardized machine processing times with little variation (Finch and Cox, 1986).

Given these unique characteristics, the adaptability of the JIT system to an American production operation can be questioned (Rees et al. 1987). In recent years, these doubts have been somewhat dispelled as numerous US firms have been successfully applying JIT principles (Huang et. al, 1983). A recent survey demonstrates the extent and nature of the emulation of Japanese practice in the U.K. and U.S. Voss and Robinson found 57 percent of a sample of 132 companies are implementing or planning to implement a JIT program (Sepehri, 1986).

Background of the Problem

According to the National Productivity Committee and the U.S. Department of labor, during the past two decades, the U.S. has had a lower average rate of productivity, lower product quality, and decrease in the share of export compared to their Asian counterparts. There has been much speculation about the causes of problems that western manufacturers have had such as: an increase in the price of crude oil, rising government regulations and intervention, union resistance, and foreign cheap labor. However, a study conducted by McKinsey and Co. stated that only 15% of the variables affecting productivity are external to the firm, and 85% are internal and under the control of management (Mann, 1971).

Most intellectuals believe one of the main reasons for the problems is the difference between shop floor control systems. Traditional western industries use a push type of production control such as Material Requirement Planning (M.R.P.) to indicate information on the timing and quality of production required in their job shop environments. Another shop floor control system is the JIT/Kanban system. These systems strive for continuous improvement by adjusting to the dynamic behavior and randomness of the production environment. This randomness in the production system is attributed to processing time variability, machine failures, tool unavailability, worker absenteeism, demand variability to name a few.

It is believed that the Kanban operated production line has better shop floor control than the push system, especially with respect to the clear control of location and the amount of inventory at each location. In systems where high variability is prevalent, there is a need to study and analyze the effect of Kanbans on the production environment. This should be done before actually implementing Kanban system so that management can correctly infer system behavior and improve upon the present parameters. This research shall explore the above concepts in detail. The objectives of this research are stated briefly in the next section.

Research Objectives

The purpose of this thesis is to study the Kanban controlled production system, with subcell scenarios, under dynamic operating conditions. The study will provide a greater understanding of the mechanics of a production line operated under Kanban control.

It can be intuitively stated that variability would result in increased Work-In-Process (WIP), backorders, overtime, system instability and the deterioration of other performances measures. Any assertion about the degree of change in performance measures, however, cannot be confirmed until real world systems are studied. Knowledge of the dynamic behavior of the Kanban system under variable environment offers the potential of determination of important design parameters to achieve optimal performance.

Many studies have been conducted on the various aspects of Kanban; this research, however, is different from the other studies in two important respects. The primary difference is the layout structure of the facility that has been modeled here. Most of the previous studies have used a simple three or four station assembly line where the job flows from one end to another and a few studies have considered a job shop type facility. According to the available literature, no study has been done which considers the interaction between the sub-cells and the assembly line, as this research will do.

It appears reasonable to assume that the very presence of this important component may significantly affect system performance.

In order to study the significance and influence of subcells, a manufacturing facility is considered where the main line is fed not only at one extreme end (first station) but also at other points by other manufacturing cells. In practice, a large number of real world manufacturing facilities have cells for producing components that are consumed at various stages of the main line. This renders the results obtained by previous research as potentially inaccurate and incomplete for real world facilities.

A second difference is that in this research, interaction among the stations on the main line and between the main-line and subcells are studied under dynamic conditions. The objectives of most of the previous studies were focused on either finding the optimum number of Kanbans, comparing JIT with MRP, or modifying the Kanban system. Few of the studies considered the effect of variability in the system. Moreover, in this study, the number of Kanbans has been considered as an independent variable. Most other previous studies have considered it as a decision variable.

The independent variables considered are demand variability, processing time variability, machine breakdown and one of the management controlled parameters viz. number of Kanbans. These variables are considered because they are the main causes of the fluctuations in any manufacturing operation. The performance parameters considered are cost, production lead time, machine utilization and material processing lead time.

A full factorial design is employed for designing the experiment and analyzing the results. Causal relationships between dependent and independent variables are tested using hypothesis testing. Conclusions are arrived at by utilizing the appropriate statistical tools.

Importance to Practitioners

Hall (1983), Monden (1981), and Schonberger (1983) have shown that a JIT system using Kanbans utilizes productive resources more effectively . Therefore, a research study that enhances the system knowledge and logic would be of significant value to practitioners. This is an explanatory research; the system considered demonstrates the mechanics of the Kanban system, though it may not reflect complex industrial applications.

The idea of assisting management in procuring the appropriate actions for Kanban implementation is not unique to this study, but perhaps the approach and scenario are. Due to an infinite number of possible real world configurations the results of this research can be generalized to many situations but is directly representative of few.

Organization

This thesis is divided into five chapters. The first chapter is a general introduction chapter, and it covers briefly the outline of Kanban/JIT systems, and the purpose of this research.

The second chapter is divided into two sections. The first section is the literature review which gives brief accounts of what has been done in the JIT/Kanban field. The second section gives description of the JIT philosophy, the Kanban system and its operation and how this thesis has evolved.

The third chapter briefly describes the methodology, assumptions, and the model configuration employed in this thesis. It also gives a brief description of the simulation model, parameters considered and validation technique exercised.

The fourth chapter discusses in detail the results obtained. It describes the effect of the number of Kanbans, the effect of processing time variability, the effect of uncertainty in the customer demand, and the effect of machine breakdown.

The fifth chapter summarizes the results, recommends some ways to reduce/eliminate the variabilities in the system and suggests future research direction possibilities.

CHAPTER II

JIT/KANBAN SYSTEMS

Literature Review

Kanban was first developed by the Toyota company (Monden, 1981) where JIT production was adopted. There are two major distinctive features in this system, i.e., the JIT production and the respect-for-human system (Sugimori, Kusunoki and Uchikawa, 1977). Hall (1983) provides a good description of how Kanban works and gives some important implementation details. Schonberger (1983) has also discussed the applicability, advantages and disadvantages of single-card and dual-card systems.

The most frequently used models for analyzing the Kanban pull systems consist of simulation, mathematical and stochastic models.

In modeling a JIT/Kanban system, Huang, Rees and Taylor (1983) presented a simulation model of a multistage and multi-line production system, by a Q-GERT network. The results indicated an overall environment overhaul if a JIT was to be implemented successfully.

Ebrahimpour and Fathi (1985) developed a simulation model to study a single-cell Kanban under the cyclical demand pattern. Bard and Golany (1991), on the other hand, formulated a multi-stage simulation model of a Kanban system. He concentrated on studying the behavior of the system in adapting to change in management policies and environmentally induced uncertainties. He assumed a close proximity between the subsequent stages and therefore used only production Kanbans to study the model.

Krajewski et.al (1987), Schroer and Black (1984), Philipoom et.al (1987) developed a large simulation model capable of representing diverse manufacturing environments. Their objective was to identify the factors of the manufacturing environment that had the largest impact on system performance. They found that the performance of the Kanban system was sensitive to the manufacturing environment; the benefits of employing the Kanban system resulted from the environmental factors, not the system itself.

Lee (1987), using a simulation model, evaluated some salient parameters such as scheduling rules, the level of pull demands level, the production Kanban size, the minimum Kanban level and the significance of the job mix. His results favor the shortest processing time as a scheduling rule, and indicate that an increase in the production Kanban size causes an escalation in the output Kanban inventory level.

Sarker and Fitzsimmons (1989) modeled a Kanban pull system under different conditions. The line efficiency of push and pull systems were computed under variable processing time using the simulation models. Similarly, Gupta and Gupta (1989) and Swinehart (1991) investigated some of the unique characteristics of the JIT/Kanban system by way of dynamic simulation models. Using system dynamics concepts, the behavior of the system under the stimulus of various exogenous factors is demonstrated.

Meral and Erkip (1991) simulated a non-Japanese environmental setting to investigate the implementability and success of JIT in that setting. Crandall and Burdwell (1993) designed a simulation experiment to study the effect of reduced WIP on throughput, lead time and utilization. He concluded that reducing allowable WIP and process variability can increase throughput and utilization, and thereby reduce lead time.

Mannivanan and Pedgen (1988) designed a rule based simulator for modeling JIT manufacturing systems. The user interacts with the simulator and provides input data related to the JIT system and the simulation experiment. The simulation model is then generated automatically. Mejabi and Wasserman (1992) implemented new language constructs to allow the important features of Kanban to be expressed as extensions of an existing simulation language (SIMAN).

Hall (1983), Huang, Rees and Taylor(1983), Finch and Cox (1986), and Krajewski et.al. (1987) pointed out that the Kanban scheme is inappropriate under dynamic environments due to its strict requirements with respect to repetitive environments. On the other hand, Gravel and Price (1988) pointed out the feasibility of the Kanban system in job shop environments. In their model, however, the processing time and set-up time, the essential arguments of Kanban adaptability to job shop environments, were assumed to be constant and negligible respectively.

Many analysis were conducted in mid 90's to determine the optimum number of Kanbans using mathematical programming. Davis and Stubitz (1987) determined the number of Kanbans in each station for optimal performance through response surface methodology and simulation in a production environment which neither represents a pure flow shop nor contains balanced production processes. Rees et.al (1987) formulated a methodology to dynamically adjust the Kanban number by using forecast demand and estimated lead time. They concluded that if conditions in the shop change very rapidly, than these shops should not implement JIT.

Miyazaki, Ohta and Nishiyama (1988) used mathematical programming to derive formulae to calculate average inventory yielded and minimum number of Kanbans for a fixed interval withdrawal Kanban. These formulae are based on given variables such as: container capacity, safety stock level, hourly demand of materials and lead time for delivery. Philipoon et.al (1987) investigated the factors that influence the Kanban number.

Bitran and Chang (1987),Bard and Golany (1991) focused on the operational control problems associated with determining the optimal number of Kanban. The approach is suitable for a JIT system since the repetitive environment is deterministic; however, it might not be feasible to apply when a dynamic environment is encountered.

Li and Co (1991) determined the optimal number of Kanban at each stage of production through dynamic programming. Askin, Mitwasi and Goldberg (1993) addressed the issue of the number of Kanbans needed for each part type with the objective of minimization of holding and back-order cost. A stochastic model was developed and results were compared with the help of simulation.

Kimura and Tereda (1981) modeled multi-stage series process with a single item using mathematical model. They provided several equations for the Kanban system and found that when unit ordering quantity is less than production quantity the production fluctuation in the succeeding stage is transmitted to the preceding stages in the same pattern. Rees et.al (1989) compared an MRP lot-for-lot system and a Kanban system in an ill-structured production environment. It was found that the MRP lot-for-lot system was more cost-effective than the Kanban system (though not when variable processing time is present) because the MRP system carried less inventory and required fewer setups.

Kim (1985) developed a periodic pull system as an alternative to a Kanban system in which a single product line with stochastic demand is considered. Karamkar and Kekre (1988) modeled both single and dual card Kanban cells and two stage Kanban systems as Markovian processes. They studied the effect of a batch sizing policy on production lead time and hence on inventory levels and cell performance.

Jordan (1988) analyzed his queuing network by markov chain model. He approximated the service time distribution using iterative methods rather than through simulation. Similarly, Wang and Wang (1991) applied some queuing concepts and then applied a markov process approach to decide the number of Kanbans in the one-to-one case and in one-to-multiple cases.

In stochastic approaches, the pull demand and the processing time are modeled as random variables. The Markov chain is often used to describe the system behavior; thus poisson process arrivals and exponential processing times are the general assumptions (Mitra and Mitrani, 1990; Deleensynder et.al, 1989; Buzacott, 1988).

Tayur (1990) studied Kanban controlled series manufacturing systems analytically through non-markovian model. They developed some theoretical results- dominance and reversibility, that characterize the dynamics of these system. He showed that to maximize the throughput with a fixed number of cards, all of the machines should be placed in a single cell.

Spearman and Zazanis (1992) presented a new integrated pull system called Constant WIP (CONWIP). Results indicated that such a pull system has better performance characteristics than that of push system. Similarly, Hodgson, Deleersynder, O'grady and Savva, (1992) developed a Markovian model to integrate Kanban type pull system and MRP type push systems. The results indicated that the push/pull approach had lower inventory levels and a better response to demand changes than the pure pull system. The integrated approach seemed to work fine as it combined many of the advantages of MRP approach while retaining much of the simplicity of Kanban/pull systems.

Major Types of Shop Floor Control Systems

Production control on the shop floor level can generally be classified as either a push system or a pull system (Karamkar 1986, Harhen and Shivan 1988).

Push System

In a push system, the information flows from the beginning of the production line to the end of the line as shown in Figure 1. A multi-period master production schedule of future

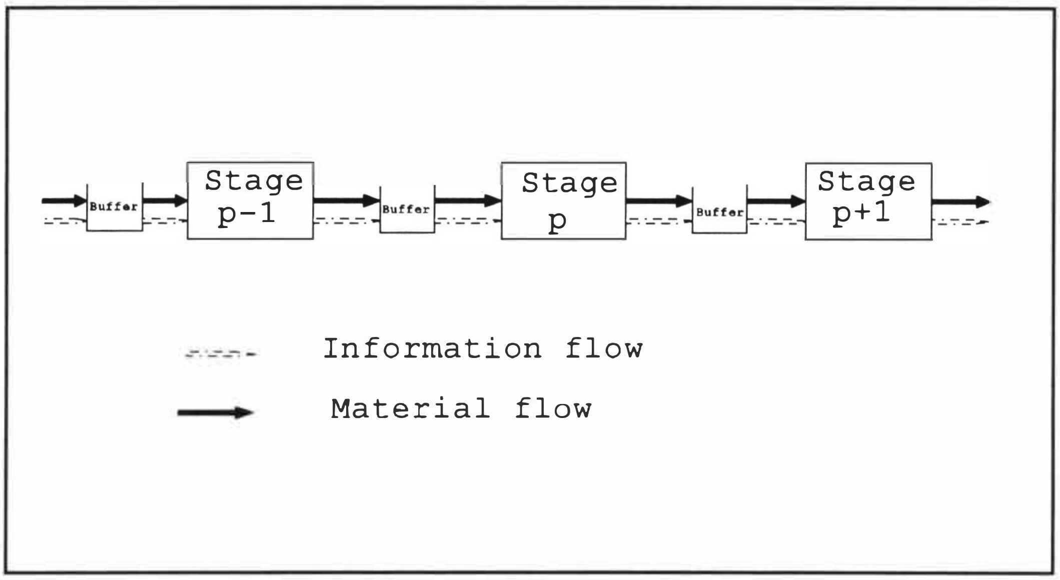

Figure 1. Push (M.R.P) System.

Source: The performance of push and pull systems: a simulation and comparative study, Sarker and Fitzsimmons, IJPR, 1989 demands (consisting of forecasted demand and the order for that period) for the company's products is prepared. A computer explodes that schedule into detailed sub-schedules for making or buying the component parts. The demands are placed at the first stage and the production at this stage starts when the required raw materials arrive. Once the job is finished, it is moved to the next stage for further processing as depicted in Figure 1. The production activation of the next stage is triggered by the items released from the preceding stage. In this way, the production of each job in the current process is 'pushed' from its up-stream process. The name given to this push system is material requirement planning (MRP).

By definition MRP is a JIT system since it attempts to offset production in time by the exact lead time needed to produce the orders. It has been noticed that MRP often fails in accomplishing its desired end. Some specific reasons for the failure are: (a) the inability of firms to impose the organizational discipline necessary to maintain information at a high level of reliability; (b) the assumption of production lead time to be fixed, known by item, and independent of facility loading, batch sizing policy, production mix and order release activity (Karamkar 1986); (c) erosion of the close association between parts requirements and end product schedules because of big lot sizes and long lead time (Schonberger, 1983); (d) high in-process inventory levels to cover incorrect forecasts, drastic changes in demand, and snags in production resulting in unnecessarily high carrying costs (Sarker and Fitzsimmons, 1989); and (e) no improvements with regard to lot size and the timing of processing because of the complexity in computing optimal production plans in detail (Kimura and Terada, 1981).

Pull System

In a pull system, the production activation of a stage is triggered by the request of the subsequent stage. Figure 2 shows the information and material flow in a pull system.

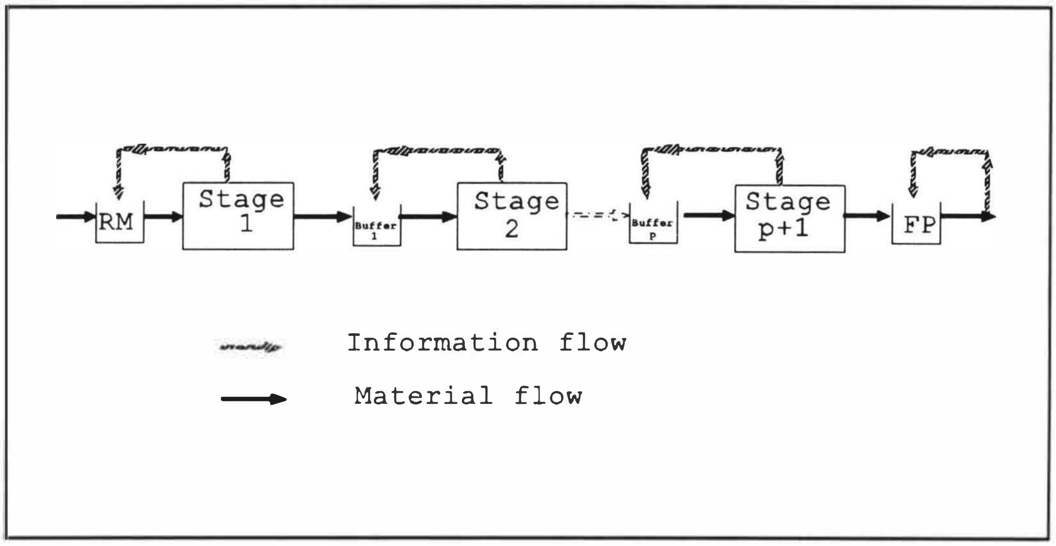

Figure 2. Pull System.

Source: The performance of push and pull systems: a simulation and comparative study, Sarker and Fitzsimmons, IJPR, 1989

As opposed to a push system, a demand is placed at the end of the production line. When a demand arrives at the final stage, components for producing the product are checked to determine if they are available. If desired components are available, the production of this stage starts; otherwise, it issues a request to the previous stage for the required parts. A similar procedure is followed backward through each production process till the beginning stage is reached. In this manner each job in the current process is pulled from its down-stream process. Make-to-order, Order point-Order quantity (OP,OQ), Base stock and JIT/Kanban are examples of pull systems (Sarker and Fittzsimmons 1989).

Just-in-Time Philosophy (JIT)

JIT is defined as an approach to achieving excellence in a manufacturing company based on the continuing elimination of waste (waste being considered as those things which do not add value to the product). In a general sense, JIT refers to the movement of materials at the necessary place at the proper time (Kupferberg, 1988). The implication is that each operation is closely synchronized with the subsequent ones to make such efficiency possible. JIT has been described as a 'tool box of techniques'. What is unique about this system is not the ingredients or pieces that are in the tool box but rather, how these pieces are put together.

Core Elements of JIT Philosophy

Over the past decade, as the customer service viewpoint has taken root, top companies have begun to adopt surprisingly new practices in operations management. These new practices are founded on a common set of JIT principle, customer service, and competitive guidelines (Moore, 1973):

1. Get to know the customer and the competition.

2. Cut WIP, throughput times, flow distances, and space.

3. Reduce setup time, processing time and lead time.

4. Manufacture and deliver at the customer's use rate; decrease cycle interval and lot size.

5. Cut the number of suppliers to a few reliable ones.

6. Make it easy to make/provide goods or services without error the first time (zero defect program).

7. Create cells and flow lines (Focused plant layouts).

8. Cross train for mastery of multiple skills.

9. Delegate authority and responsibility to the workers.

10. Maintain and improve present equipment (Preventive maintenance).

11. Become dedicated to continual, rapid improvement.

Benefits of JIT System

Five major benefits of pull/JIT systems are: (1) minimized in-process inventory and reduced fluctuations of inventory, (2) simplified inventory controls, (3) no amplified transmission of demand fluctuations from stage to stage, (4) raised level of shop control through decentralization, and (5) reduction of defects (Huang et al. 1983, Sarker and Fitzsimmons, 1989).

These benefits are only realized, however, if JIT philosophy and techniques are fully understood. Voss and Robinson conclude

> ...few companies are actually making a serious attempt to implement JIT. Where they are implementing JIT, they are implementing just a subset of JIT, and the data suggest that companies are focusing on the easy to implement techniques rather than those giving the greatest benefits. Those companies lose sight of the overall and continuous improvement philosophy - the leading cause of failure (Sepehri, 1986, Page 256).

Kanban System

This section shall discuss about the Kanban system and how it functions. It is important to understand the basic premises behind this system before one proceeds into a detailed analysis. The Kanban system is a "production control and information system that harmoniously controls the production of the necessary products in the necessary quantities at the necessary time of every process of a factory and also among companies" (Kupferberg, 1988, Page 441).

A Kanban is a card which contains information such as the job type, the quantity of parts to carry, Kanban number, preceding work station, succeeding work station and the Kanban type. Figure 3 shows a Withdrawal Kanban (WK) and a Production Kanban(PK). A Kanban system acts as the nerve of a JIT production system. It directs materials just in time to succeeding work-stations, and passes information regarding what and how much to produce for preceding work-stations (Wang and Wang, 1991).

The objective of a Kanban system is to respond to demand just in time and to minimize inventory obsolescence. Kanban systems provide a way to achieve these objectives with a very

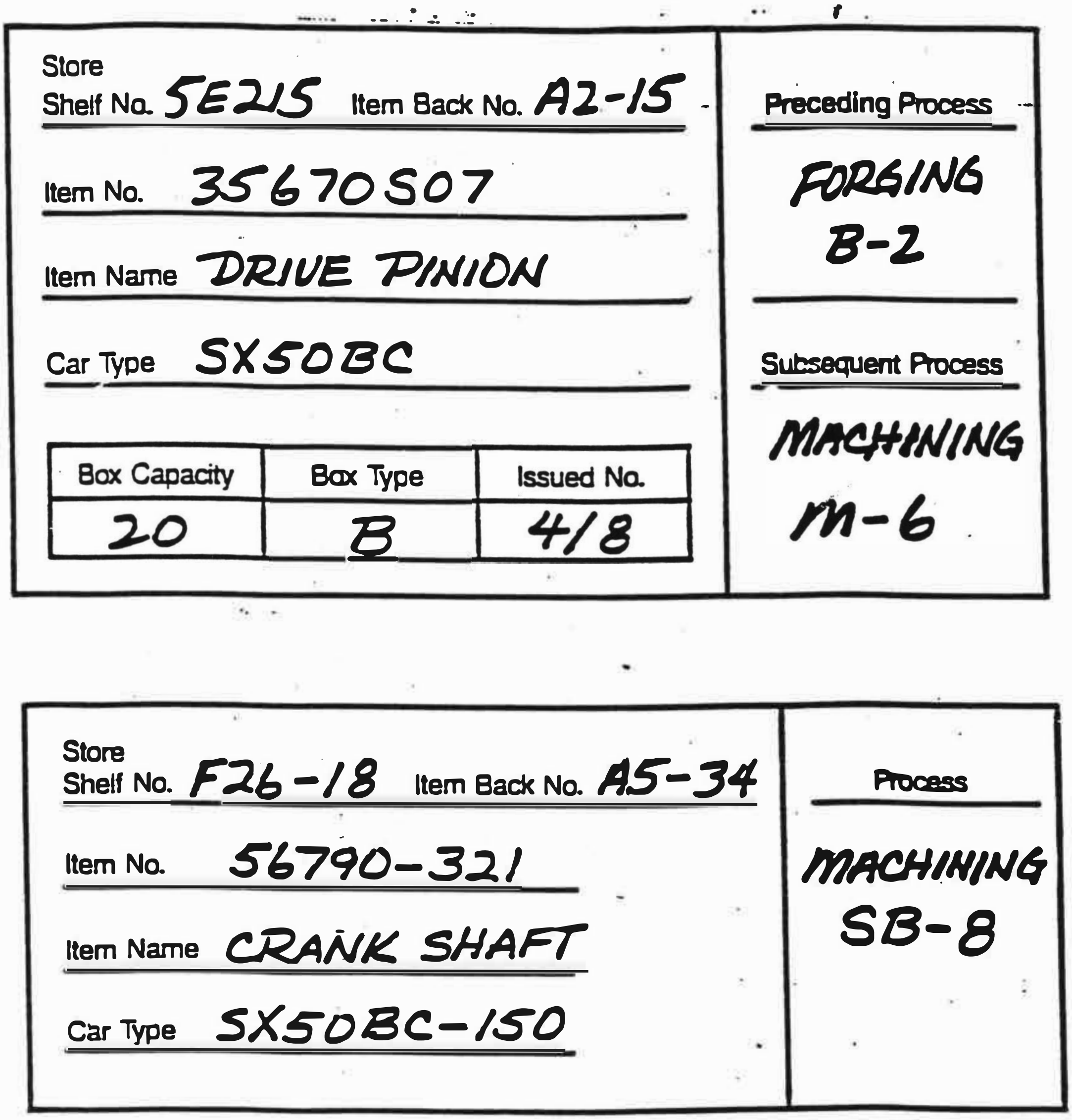

Figure 3. Typical Layout of Kanban Cards.

<u>Source</u>: Adaptable Kanban System Helps Toyota Maintain Just-In-Time Production, Y. Monden, Industrial Engineering, May 81.

simple and inexpensive shop floor control system (Askin, Mitawasi and Goldberg, 1993). Kanban systems reduce significantly the paperwork, the overhead necessary for the operation of the facility and control of the inventory. These features of the Kanban system make it robust in the sense that it tends to absorb and adapt to uncertainties without requiring continuous management intervention (Bitran and Chang, 1987). However, Kanban system requires container throughout the shop to make the pull system work. In case of big container size and large lead times, Kanban system would result in lot of in-process inventory.

There are two kinds of Kanbans mainly used: withdrawal Kanbans (WK) and a production Kanbans (PK). A WK (refer Figure 3) specifies the kind and quality of product which the subsequent process should withdraw from the preceding process, while a PK (refer Figure 3) specifies the kind and quantity of the product which the preceding process must produce. Other types of Kanbans which are sometimes used are subcontract Kanbans, emergency Kanbans, etc (Monden, 1981).

Single-Card Kanban System

Most of the companies that claim to have a Kanban system have a single-card system. The single card that they use is either a withdrawal Kanban (WK) or a production Kanban (PK). It is easy to begin with a WK system and than add PK later if it seems beneficial.

In single-card Kanban, parts are produced and bought according to a daily schedule, and deliveries to the user are controlled by WKs. In effect, the single-card system is a push system for production coupled with a pull system for deliveries.

Single-card Kanban does not employ a stock point for incoming parts. Instead, parts are delivered right to the point of use. Also, the stock point for parts just produced tends to be larger than that for dual-card Kanban. The reason for the enlarged stock point is that it holds stock produced to a schedule. The schedule pushes semi-finished parts into the stock point even when the subsequent machine has been slowed or halted as a result of production or quality problems (Schonberger, 1983).

Dual-Card Kanban System

This research employs dual-card Kanban system. Figure 4 exhibits outline of the part flow and the card flow and step by step Kanban processing. Starting from the subsequent process, the various steps utilizing the Kanban are (refer Figure 4):

Step 1. The carrier of the subsequent process goes to the store of the preceding process with the WKs and the empty pallets. It is done after a fixed interval of time.

Step 2. When the subsequent process carrier withdraws the parts at the preceding store, he detaches the PKs

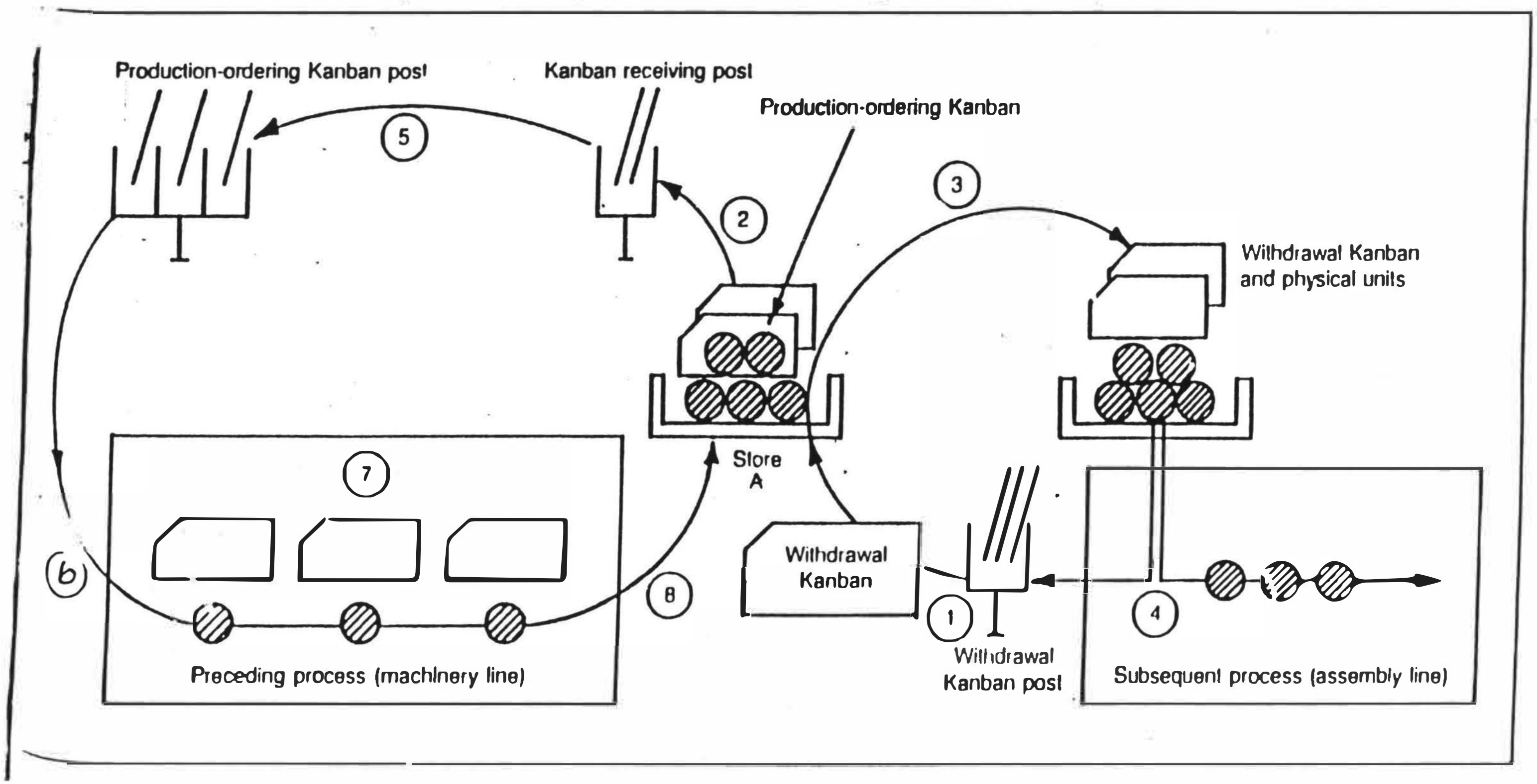

Figure 4. Steps Involved in Using the Two Kanbans.

<u>Source:</u> Adaptable Kanban system Helps Toyota Maintain Just-In-Time Production, Y. Monden, Industrial Engineering, May 81, page 31

which were attached to the physical units in the pallets and places these Kanbans in the Kanban receiving post.

Step 3. He leaves the empty pallets at the place designated by the preceding process workers. For each PK that he detached, he attaches in its place one of his WKs. When exchanging the two types of Kanbans, he carefully compares the WK with PK for consistency. When work begins in the subsequent process, the WK must be put in the WK post.

Step 4. In the preceding process, the PK should be collected at a certain point in time from the Kanban receiving post and must be placed in the PK post in the same sequence in which it had been detached at preceding store. Production of the parts progresses according to the ordinal sequence of the PK in the post.

Step 5. The physical units and the Kanban must move as a pair when processed. When the physical units are completed in this process, they and the PK are placed in store, so that the carrier from the subsequent process can withdraw them at any time (Monden, 1981).

Such a chain of two Kanbans must exist continuously in many of the preceding processes. As a result, every process will receive the necessary kind of units at the appropriate time in the necessary quantities, so that the 'just-in-time' ideal will be realized in every process. Therefore, the chain of Kanbans will help realize the line balancing for each process so that it will produce its output in accordance with the cycle time. In a pure pull system, workers do maintenance or work on improvement projects, rather than producing more than required, when there are no PK in the dispatch box.

Kanban Rules

Monden (1981) has mentioned some rules which are followed in this research for the effective implementation of Kanban. These rules are:

1. The subsequent process withdraws the necessary products from the preceding process in the necessary quantities at the necessary point in time.

2. The preceding process produces products in the quantities withdrawn by the subsequent process.

3. Defective products are never conveyed to the subsequent process.

Information Processing of Kanban

Kanban, as an information processing tool, flows physically in the reverse direction to the material flow as manifested in Figure 2. Hence, in a Kanban system, the total information processing time is from the time when a Kanban is removed from a container until the time it is presented to a preceding stage for the necessary action, either withdrawal or production. A longer Kanban lead time results in a larger number of Kanbans, a larger amount of in-process inventories, and a slower response to the dynamics of material flow (Mannivannan and Pedgen, 1988).

Since transportation time between stations has been assumed negligible in this research, the information processing time for WK depends only upon the Kanban pick-up frequency.

Kanban as a Productivity Improvement System

The number of containers employed should be carefully decided upon by the management. In non-ideal conditions, the number of Kanbans required are approximated through trial and error. Incremental improvement of the process enables production manager to remove some Kanbans, thereby deliberately exposing some new problems. Japanese deliberately remove buffer inventory (or Kanban) in order to expose the problems which were concealed under the 'inventory shield' and solve them (Schonberger, 1983; Sugimori et al. 1977). These problems will lead to new solutions, causing an additional reduction in process variability. The ultimate goal is to make every defect visible by gradually removing that part of inventory that served to protect the master production schedule against this source of uncertainty. The above philosophy is depicted in Figure 5, where water level is analogous to the WIP level and boulders under the water are analogous to the 'unveiled problem'.

Kanban Applicability

Kanban is feasible in almost any plant that makes goods

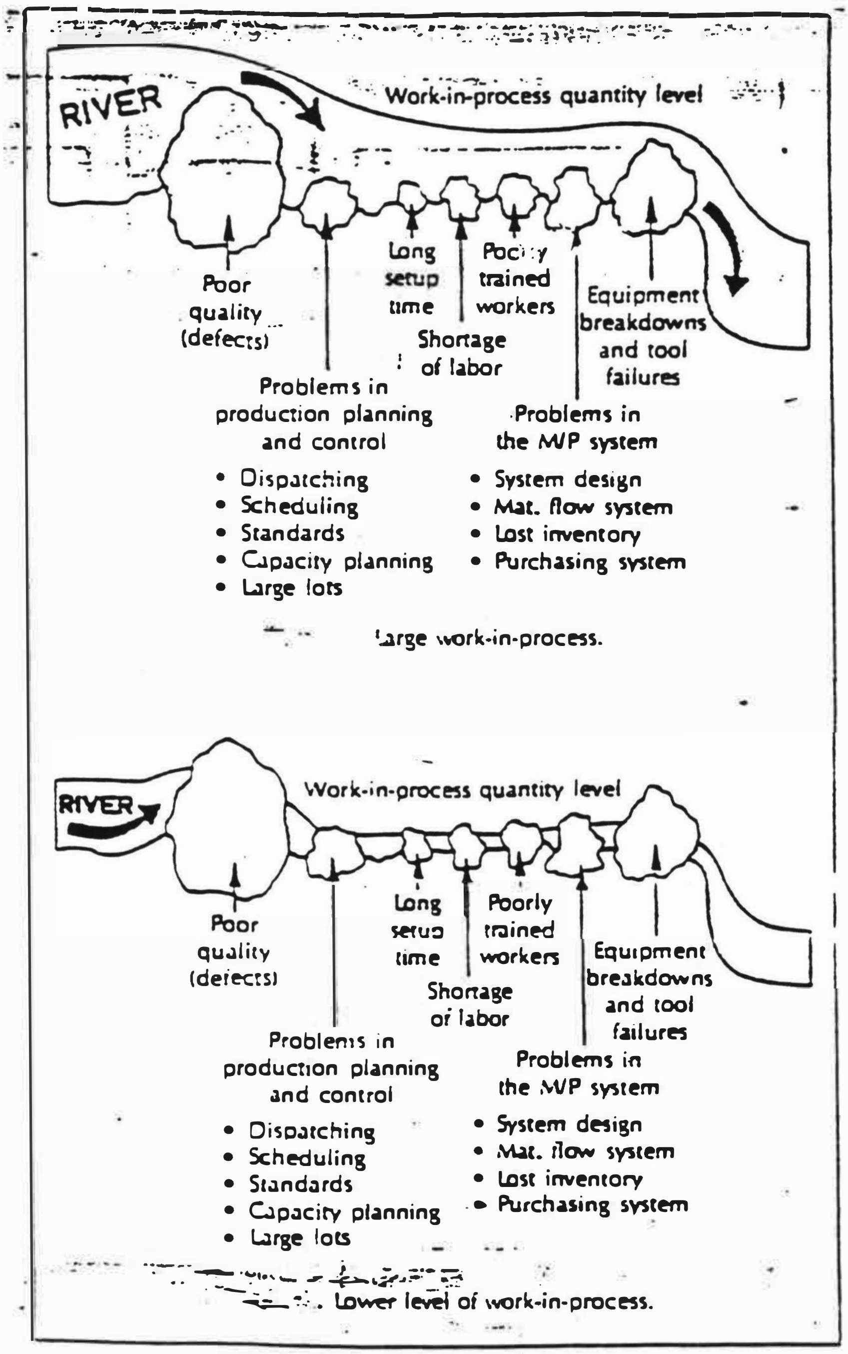

Figure 5. Productivity Improvement System.

Source: Microcomputer analyzes 2 card Kanban System for Just-In-Time small batch production, Schroer, B.J. & Black, J.T., Industrial Engineering, May 1984, 54-65 in whole (discrete) units (but not in the process industries). It is considered to be beneficial only within certain constraints:

1. Kanban should be an element of a JIT system. Kanban gives good results when setup times and lot sizes are low because it allows for fast 'pull' of parts from producing work centers.

2. The parts included in the Kanban system should be used every day (Hall 1983).

3. Very expensive or very large items should not be included in Kanban - such items are costly to store and carry (Schonberger, 1983).

Therefore, when choosing a Kanban system, managers must consider the tradeoffs among the length of the planning horizon, the fluctuation of the demand pattern, the degree of overhead and management intervention, and the amount of extra inventory that might be implied by an easy-to-manage system (Bitran and Chang, 1987).

Kanban Systems Under Repetitive and Dynamic Environments

Under a repetitive manufacturing system, the products are made repetitively under stable demand. The Kanban approach works well in such cases when the variety of products is low, the production is highly repetitive, and the demand is fairly constant.

When the monthly demand changes, one would expect that the total number of Kanbans per month would also change. Companies which have completely understood the concept of JIT do not have to routinely adjust the number of Kanbans from month to month for at least three reasons: (1) they have a large market share and hence demand variations from the forecasted value are a small percentage of the total, (2) they have cross trained workers whom they are able to switch from work-center to work-center to mitigate temporary bottlenecks and (3) their JIT shops are so well run that they can handle day-to-day problems as well as variations in demand (Rees et al., 1987).

Companies which have implemented Kanban systems, but do not have the above structure, might face difficulties under a dynamic environment. Due to stringent restrictions with respect to repetitive environments, this kind of Kanban scheme is not considered to be appropriate under dynamic environments, as pointed out by Hall (1983), Finch and Cox (1986), and Krajewski et al. (1987). With variable demands and variable processing times in dynamic environments, it is difficult to set the master schedule, and thus, line balancing and synchronization, as in the repetitive system, are impossible to attain.

A corporation could change the dynamic environments toward the repetitive system and adopt the Kanban control discipline. However, this would require a huge overhaul of the system (Huang, Rees and Taylor, 1983; Finch and Cox, 1986) which is not practical in many cases because this would require full-scale restructuring. To gain insight into the behavior of Kanbans system under dynamic environments, the above situation is simulated. Modifying the original Kanban operation to be useful under dynamic environments seems feasible, though not all of the repetitive systems' benefit could be achieved because of the environmental variations.

CHAPTER III

METHODOLOGY

In this study, the application of a Kanban control system to a semi-assembly type production line has been analyzed under a dynamic environment. Analysis of efficiency, effectiveness, and adaptability of the JIT/Kanban system in the above mentioned environment have been done. Characteristics of a JIT system such as respect for humanity and quality circles are not being specifically considered since the purpose of this research is to focus on just one aspect of JIT: Kanbans.

Real world situations are too complex to be modeled. To make the model comprehensible and simple, a few assumptions were made.

Assumptions

These assumptions were in no way intended to limit the applicability of the model, but rather were made for the model manageability.

1. The manufacturing line is dedicated to three products (focused factory).

2. Transportation time between stations is negligible.

3. Number of production Kanbans (PK) and withdrawal Kanbans (WK) at any stage are equal.

4. There is a continuous and infinite supply of right quality raw material at the first station on the line.

5. As soon as a production Kanban gets free, it is sent to the PK post. PKs are removed form PK post on FCFS (First Come First Serve) basis.

6. When the first piece of a full container is used in succeeding production process, the withdrawal Kanban attached to the container is detached and kept aside. At the end of a fixed time period, all the Kanbans detached during the time period are collected and sent back to preceding process. These types of Kanbans are referred to as Fixed Interval Withdrawal Kanbans (FIWK).

7. Total number of Kanbans circulating between preceding and succeeding process is unchanged over the period of time (i.e. for a single run).

8. Each stage of main line has only one work-center. The number of machines in each subcell varies.

9. Partial preventive maintenance is present.

10. Since the Kanban size is assumed to be small compared to the quantity produced, demands are assumed to be coming in multiples of the Kanban size.

11. The line is designed as an unpaced (asynchronous) line in terms of item movement between work stations.

12. The number of defective units which leads to yield uncertainty in production systems is very low in pull production system. Hence, it is assumed that no yield uncertainty exists

in the JIT production line examined.

13. Supplier related issues are not included in the model.

14. As demand is assumed to be externally generated and must be eventually satisfied, back-orders have no limits.

As mentioned above, the Dual-card system has been used. The reasons for choosing Dual-card system are discussed in the next section.

Why a Dual-card System

Reasons for choosing the Dual-card system are:

1. Mitra and Mitrani (1990) showed that the two-card Kanban-controlled line has a greater expected output than a single card system. The reason given for this behavior is that the dual-card Kanban controlled line has a greater capacity for inter-stage inventory than with single card systems. A two-card controlled line allows for a maximum of 2N units (where N is # of Kanbans) in inter-stage buffer. One-card systems, however, only permit a maximum of N+1 units in inter-stage buffer.

2. Dual-card systems are doubly effective in that they have the ability to improve production by removing Kanban to expose and solve problems. Unfortunately, single-card systems cannot employ this feature because there is no control on the number of full containers of a given part type.

3. As indicated by Schonberger (1983), dual card systems effectively handle the compound effect of the following: (a)

a large number of parts, (b) variable occurrence factors and (c) multiple stages of manufac-turing, by tuning production of each part number to the ups and downs of succeeding stages' output rate.

4. Dual-card systems have better information sensing and material handling capabilities.

The Manufacturing Flowline

The manufacturing line considered was very generalized in the sense that it could represent the fabrication of a part needed for an assembly operation or the completion of an entire job from raw materials to finished goods. Different aspects and features of flowline are discussed below.

Model Configuration

Figure 6 depicts the configuration of the model employed for this analysis. The basic manufacturing environment consists of a 4-stage production system and three subcells which feed the main production line. The main line consists of 4 machining centers working in series. The first station converts raw material into components, which pass into the first inter-stage inventory. The middle stages do processing and assembling operations on the components from the preceding stages. These stages take material from subcells, as shown in Figure 6. Work-in-process is stored in the same stage output buffer or succeeding stage input buffer depending upon the availability of the Kanban and the storage capacity. The last stage performs the final operation: converting WIP from the preceding stage into end items which are stored in the end item inventory or shipped out depending upon demand.

When a customer places an order, the manufacturer checks the availability of parts. Parts not on hand are pulled through, or expedited. Parts pulled send a trigger which initiates the production process. Every station produces to replenish the goods consumed, thereby releasing cards (or containers). These cards trigger production in the preceding stage.

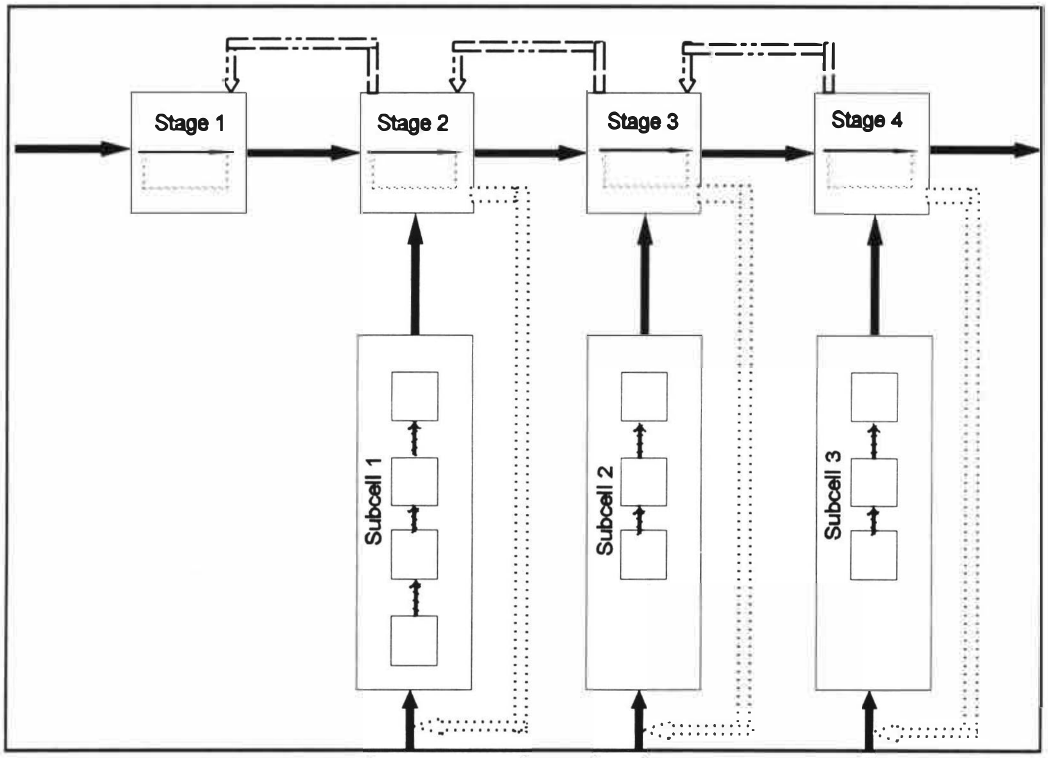

Figure 6. Model Configuration.

As shown in Figure 6, the main line has four production Kanban loops and three withdrawal Kanban loops. A fixed number of Kanbans (N) circulates in each loop as production goes on. No withdrawal Kanban has been considered between main-line stations and subcells. The presence of WIP at the main station work-center signals the subcell for the material. Each subcell has a fixed number of PKs (M) which loop from the PK post of subcell to the main line and back to the PK post of the subcell.

Dedicated Kanban scheme is used, which means that Kanbans are dedicated to each product. Advantage of this system is that such a Kanban scheme simplifies the operation control if the number of product types produced in the system is less. But, in case of determining optimum Kanban number, the solution search space grows exponentially as the number of product type increases.

Subcells

Subcells utilize a CONWIP configuration (constant work in process) (Spearman and Zazanis, 1992). In this system, raw material is pulled into the subcell whenever an earlier job is completed and is then pushed between stations. This system has less congestion than a push system, and is easy to implement and control. The above description would make subcells appear as a flow shop, but the major differentiation from the flow shop environment is that for a given type of product, certain production steps may be omitted. Each finished item of each subcell follows a unique route through the subcell.

Also, the machines were assumed to have the capability of performing various manufacturing operations. These features shift subcell design slightly toward a job shop design. The subcells have been given the characteristics of both a job shop and an assembly shop in order to explore the feasibility of the Kanban system in the broadest context possible.

For the subcell, the choice of container size is 'container-for-container', i.e., for one container of main-line items, exactly one container of subcell items is required (Wang and Wang, 1991). This mode was selected because it does not require the handling of multiple containers from one stage to the next and it tends not to accumulate the inventory of work-in-process.

Previous studies have considered the Kanban approach primarily for the flow shop environment with balanced production times. Under this environment there would be no variability and the Kanban system would work just fine. These assumptions, however, do not apply to an environment employing subcell for two reasons. First, a true flow shop environment does not exist because of the different process route for each product. Second, the production times and demands for a given process are not balanced. This study shall provide a more realistic insight into the operation of such an environment.

Buffer System

Inventory buffers are established between each stage because the stages are not directly linked as in a continuous process. Detached buffers (Mejabi and Wasserman, 1992) are employed in the main line and at the mainline-subcell interfaces. In this kind of buffer, material remain there until removed by a Kanban. Flow-through buffers are employed within the subcells. Inventory resides in these buffers only while waiting for a change in the system status.

The system considered does not have any safety stock level for the WIP and the finished goods. This makes the system essentially a make-to-order production system. Also, the line configuration works in a hand-in-hand arrangement making each stage more dependent on the other stages.

Blocking Mechanism

There are two general types of blocking mechanism most often used in production systems (Berkley, 1990):

1. Communication system blocking, in which the preceding station is blocked as soon as the succeeding stations queue becomes full. The preceding station cannot begin serving a new unit until a departure occurs from the succeeding station.

2. Production system blocking, this occurs when, at the moment of service completion at a preceding station, the succeeding station queue is full. In this case, the unit is forced to wait at the preceding station until a departure occurs from the succeeding station. During this time, the preceding station remains idle and cannot serve any other units which might be waiting in its queue.

In this research, communication system blocking is used because it has a better information processing capability than production system blocking. Finished items from a station experience blocking when there are no WK available at the post. These blocked parts wait in the preceding station output buffer. A station experiences blocking whenever the PKs at its disposal are exhausted. Production will not resume until departure occurs from its output buffer.

Product Structure

In the hypothetical production operation which has been employed as an example in the simulation model, three end items, A, B, and C, are manufactured. Figure 7 shows the product structure for the three end items and the various component

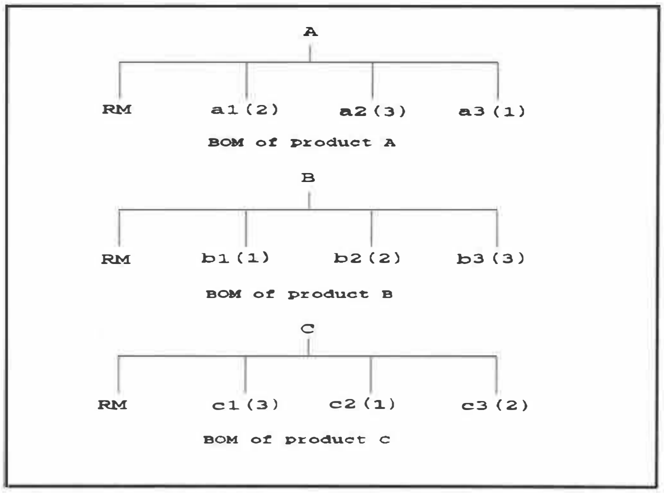

Figure 7. Product Structure.

parts required to produce them. It can be noticed that every end product has only 2 levels. For example, one unit of A requires one unit of RM1, two units of a1, two units of a2 and two units of a3. Item B and C are manufactured in a similar manner.

Simulation as an Analysis Vehicle

In this research, simulation is used as an analysis vehicle to determine the effect of the variability of critical elements on a Kanban controlled system. Simulation can easily handle a greater number of parameters and alternatives than other decision making techniques. Through the aid of simulation, many decisions which were previously based on intuition can now be based on a decision making technique, thus improving the quality of decision (Walde, 1991).

A few specific reasons for choosing simulation over other analysis tools are as follows:

1. Ease of modeling- For the model and product structure described in the previous section, simulation is the simplest method for modeling the situation. It would take much more time and effort to model the same situation through any other tool. Moreover, even under the simplest scenarios, the mathematical models become very cumbersome and difficult to solve.

2. Flexibility- A simulation model can be easily altered to determine the results of changes without disrupting the system. In some other modeling tools, relaxing a assumptions requires changing either the whole or part of the framework.

3. Ease of Experimentation- The model coded permits easy

experimentation. Parameters can be varied very easily and the combined effects as well as effects of individual parameters can be easily studied.

4. Ease of use- Simulation software is very simple to use. The coding is comprehensible and can be easily related to the model.

5. Comprehensible output- Detailed output is generated by SLAM II. It gives mean value, standard deviation, maximum value, minimum value, average utilization and many other statistics on its output report. This kind of output is very difficult to obtain by any other method.

A few of the most common simulation languages are SLAM II, SIMAN, and GPSS. SLAM II has been used for modeling because it is one of the most flexible, versatile, and easy to use languages.

Model Constraints and Pull Rules

Pull systems follow certain rules and have various constraints which differentiate them from push systems. Pull system should abide by these rules if they want to reap its benefit. This model follows the rules mentioned by Bitran and Chang (1987). Some of the important rules which form the heart of the pull systems are mentioned below:

1. For a specific time period, the number of back-orders is equal to the demand left by the previous time period, plus the amount of material used by the downstream machine, less

the actual output created during the current time period. This rule describes the conservation of material flow.

2. Similarly there is the conservation of Kanban flow. This means that the number of Kanbans left at the end of a specific time period is equal to the number of Kanbans at the start of the period, plus the number of Kanbans detached from their associated containers, minus the number of Kanbans which have triggered the production.

3. Under Kanban systems, the number of containers that can be produced in a certain time period by a particular station is the minimum of (a) available detached Kanban from previous time period, (b) capacity of that station, and (c) available inventories at the immediately preceding stations.

4. The number of Kanbans detached during a given time period is determined by the demand (in containers) for that part from the upstream station during that period.

In next section, it shall be noted that these rules have been accounted for automatically within the model logic.

The Simulation Model

A simulation model using Kanbans was constructed using the SLAM II simulation language (Pritsker, 1986). It contains 35 user functions and approximately 1000 lines of SLAM code. In developing the computer model, an attempt was made to incorporate as many features of a JIT system as possible. These include the provisions of WKs and PKs and a pulling nature. The model controls the flow of components through the shop and keeps track of on-hand inventory, in-process inventory levels, and set-up costs at each work-center.

The foundations of a simulation model are the machine and the Kanban. Material is staged as input into the process and is processed into output; during the process, resources are utilized. The main-line stages and the subcell stages are modeled as resources with a capacity of one machine. The finished products of the subcells are modeled as variable capacity resources. Figure 8 shows the list of the resources that have been considered in this study. It has been observed that two issues are central to the modeling of this system. The issues are (1) handling the successful and satisfactory transitions of the Kanban and (2) interfacing the main line to the subcell. How these requirements are met is illustrated later in this section. The model is divided largely into two sections (1) The model frame- a coded model of the system being simulated, and (2) The experimental frame- a description of the conditions under which the simulation will be executed.

Model Frame Description

Five subsections have been identified as significant in the model frame: (1) Material and Kanban arrival sensing section, (2) Demand arrival sensing section,(3) Main line modeling, (4) Subcell modeling and (5) The interface between the main-line and subcells.

```
RESOURCE/OPER1(1),59,5;
RESOURCE/OPER2(1),11;
RESOURCE/OPER3(1),32;
RESOURCE/OPER4(1),39;
RESOURCE/OPER11(1),60,16;
RESOURCE/OPER12(1),60,18;
RESOURCE/OPER13(1),60,21;
RESOURCE/OPER14(1),60,24;
RESOURCE/OPER21(1),45;
RESOURCE/OPER22(1),49;
RESOURCE/OPER23(1),51;
RESOURCE/OPER31(1),54;
RESOURCE/OPER32(1),57;
RESOURCE/OPER33(1),58;
RESOURCE/RES11(1),11;
RESOURCE/RES12(1),11;
RESOURCE/RES13(1),11;
RESOURCE/RES21(1),32;
RESOURCE/RES22(1),32;
RESOURCE/RES23(1),32;
RESOURCE/RES31(1),39;
RESOURCE/RES32(1),39;
```

Figure 8. Work-Center, Machines and Subcell's Finished Product Represented as Resources.

The network has been partitioned in a manner that complements the stage structure of the production system. A brief description of several of the important network components is given here. The network model described will not be simulated and analyzed as is; rather, it will form the primary component of a module to be incorporated into a larger simulation model of a more complex, multistage production system.

In the third and fourth subsections respectively, descriptions of the main-line final stage and subcell-3 are given. The second subsection describes the order arrival and order completion; this makes descriptions employed in the second, third and fourth subsections interconnected and intermingled as demand arrives at the final stage. Descriptions of the other stages and subcells can be derived from the description given in subsections three and four.

Material and Kanban Arrival Sensing Section

A dual-card system has been used, therefore, inter-stage and intra-stage Kanban loops are present. The loops will be satisfied only when Kanban and requisite materials are available simultaneously. Whenever a Kanban is detached from the container and is sent back to its post, it seeks to become satisfied by sending out a 'message' to the material queue. Inversely, when material (container) arrives to the buffer, it sends out the 'message' to the Kanban queue.

A mechanism is provided that would allow the Kanbans (materials) to become satisfied at the next available opportunity if it cannot be immediately satisfied due to the unavailability of material (Kanban).

Every stage, except the first stage, has the mechanism, called event subroutine, to sense the arrival of Kanban and material. For the final stage, event subroutine 14 is the mechanism that keeps track of the next available opportunity for PK as well as material. A match node is used to transfer WK and material from a preceding stage to its succeeding stage.

The assumption of an infinite source of raw material makes the first stage different from the other stages in two respects: (1) no WK loop exists between the first stage and the supplier, and (2) the mechanism need not keep track of raw material.

Demand Arrival Sensing Section

The hypothetical production line makes three different types of end products. Figure 9 shows the network for demand generation and order completion. Orders for all three products have an equal probability of arriving. All orders are served from the final stage of the main-line. In the simulation model, the entities represent orders. Each order consists of only one product type. Order creation time is stored as the third attribute for computation of the time taken to complete the order; this computation is done upon the completion of the simulation run.The sixth attribute identifies the product for which the order has come. The order quantity is converted into the number of Kanbans (containers) required to fulfill the order and is stored as the fourth attribute.

Event 3 (refer Figure 9) senses the arrival of orders into the system and compares the order type with the finished product (FP) inventory. If no FP container of the type demanded

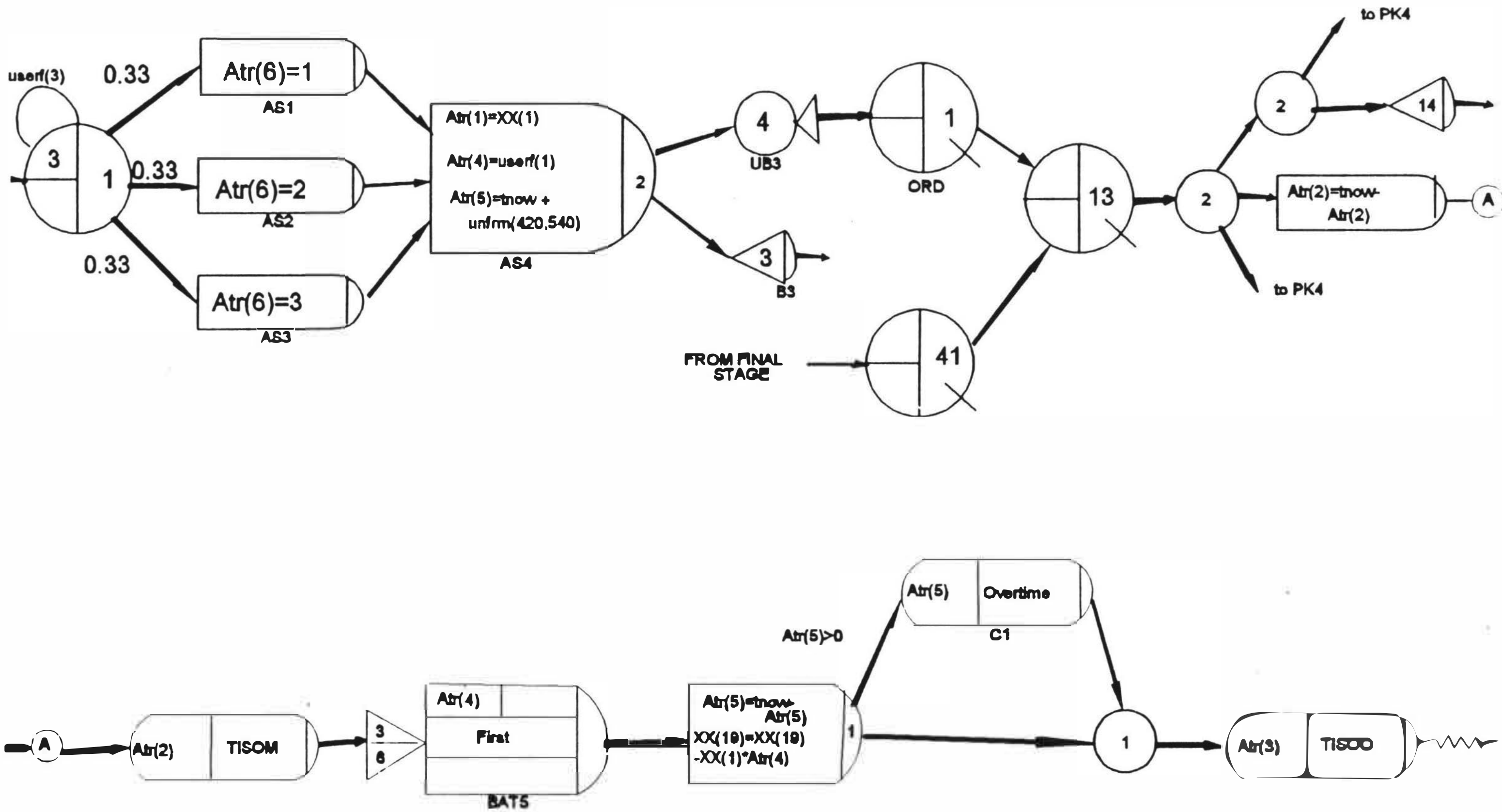

Figure 9. Network Showing Order Generation and Order Completion.

is available at queue 41, the order waits in queue 1. Otherwise, the inventory is compared with the demand requirement; if the demand is equal to or less than the available finished product inventory, the required number of containers is extracted from queue 41 and placed in queue 13, otherwise, the available containers are extracted and the remaining unsatisfied demand joins queue 1. Extracted containers of FP go through queue 13 to the collect node where statistics on the time spent by the containers in the system is collected.

At the same time, PK attached to the containers are detached and sent back to the final stage PK post (queue 37) to initiate production. Extracted containers pass into the batch node, where orders are batched according to their type (attribute 6) and quantity per order (attribute 4).Once an order is complete, it is released and statistics on the time spent by the order in the system is collected (based on attribute 3).

Main Line Modeling Section

Since the basic logic of all the work stations in the main line is similar, only a description of the final stage is given. Figure 10 portrays the main features of the network for the main-line final stage.

The PKs arriving at queue 37 indicate the need to replenish the used up containers. PKs are processed on a FCFS basis, i.e., no other PKs which are in the queue will be processed until the PK at the head of the queue is processed. Event

14 senses the presence of PKs at queue 37. Whenever a PK and a semi-finished product with the WK of correct match are available at queue 37 and 42 respectively, Event 14 triggers a withdrawal of semi-finished product and allows the transaction to move to an await node 38.

Await node 38 assures that only one Kanban (container) is released for processing when the final station becomes available. The container waits for material from subcell-3 at await node 39. After acquiring requisite materials from subcell-3, the container gets processed by production activity number 8. After processing, the station is freed for the next available container. The finished product is then stored in the FP inventory (queue 41).

When a container is released from a preceding station, the WK attached to it is sent back to the WK post (queue 36). WKs are picked up from the WK post after fixed interval of time and are transferred to queue 35. A match node matches a PK (container of semi-finished product), residing in the third stage output storage (queue 34), with a WK (queue 35).When both of these Kanbans are matched, the container is transferred to the succeeding stage (queue 42), while the attached PK is removed and sent back to third stage PK post (queue 30).

Subcell Modeling Section

Since the final stage has been explained here, it makes sense to discuss subcell-3 (the subcell feeding the final

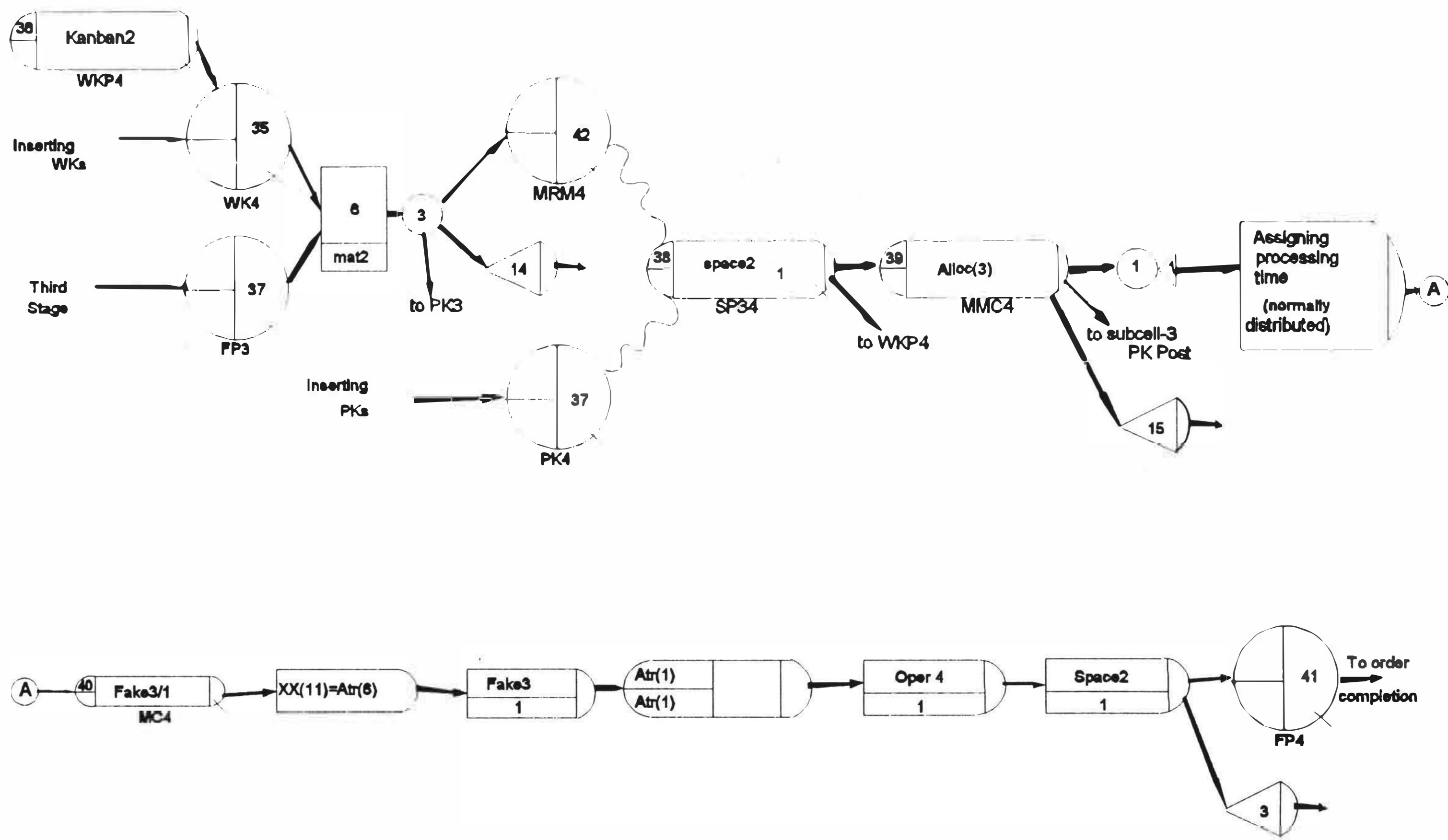

Figure 10. Network for the Main-Line Final Stage.

stage). Figure 11 characterizes the main features of the subcell-3 layout.

When the main line last stage acquires material from subcell-3, the PK attached to these containers are routed back to the subcell PK post (queue 52). Arrival of PKs is sensed by event 15. Raw material is entered into subcell-3 depending upon the type of Kanban and the availability of the necessary machine (based on the process route). The raw material container is then moved into queue 53.

Process routes for different products in subcell-3 are as shown in Table 1.

Table 1

Process Routes

Product Type	First Machine	Second Machine	Third Machine
A	2	3	-
B	2	3	-
C	1	2	3

Raw materials and Kanbans are matched based on product type (attribute 6). Once a match is found, they are routed based on the process route as shown in table above.

Movement of material through the subcell follows a certain framework. A few important things worth mentioning about this framework are:

1. Production batch size is container size (Kanban size),

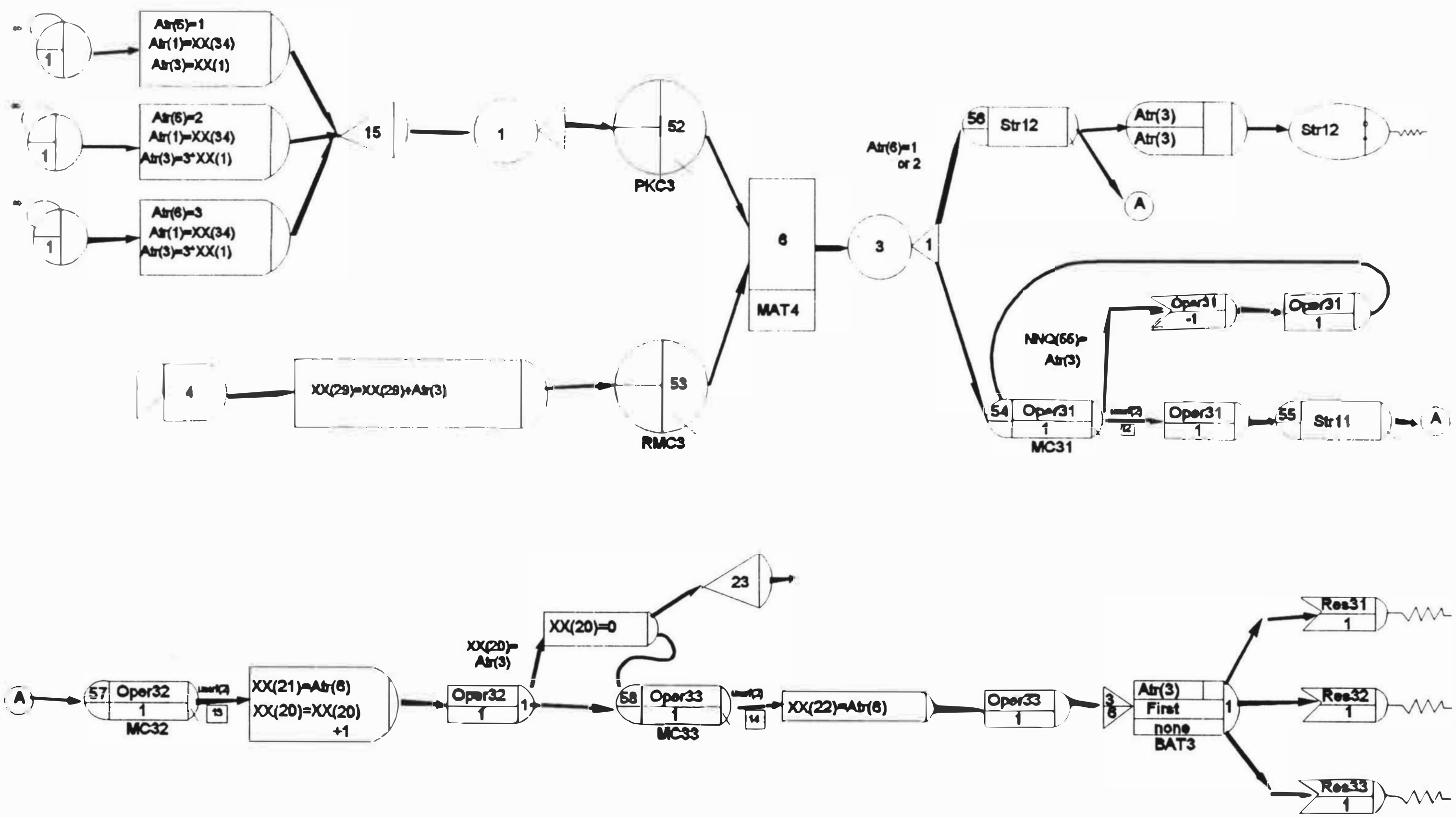

Figure 11. Network Showing Subcell-3 Layout (Subcell feeding Main-Line Final Stage).

i.e., the next container in the queue would not be processed until all the units of the current container are processed.

2. Between any two machines, there is a separate queue for every type of product, provided the process route is different. For example, as shown above in the process route table, all three types of products go from machine 2 to machine 3. Therefore, there would be only one queue between machine 2 and machine 3.

3. Queue capacity is one container of any type of product. Therefore, if the queue is full, the preceding station would experience blocking.

4. If a machine has more than one queue in front of it, then the queue is selected based on cyclic priority.

Interfacing Subcell and Main Line

This section is not very explicit in the network model. In this section, interfacing between the final stage and subcell-3 is illustrated.

The finished container joins the subcell's FP inventory, which is updated by the alter node, after getting completely processed. Await node 39 is the point where the final stage of the main-line interfaces with subcell-3. This await node has a special resource allocation feature called Allocation Command. Unfinished material in the main line cannot proceed further until it gets requisite resources from the subcell-3 (a container of finished components) and the main line (final stage work-center). When the requisite material is not available at subcell-3 FP inventory, the main line material waits for the next available opportunity. Once the desired container from the subcell is seized, the PK attached to it is sent back to the subcell-3 PK post, which serves as an order for the subcell.

Experimental Frame Description

In this study, we modeled a hypothetical process with four stages in the main line. Four, three and three machines are considered in subcell-1, subcell-2, and subcell-3 respectively.

Screening Experiment

The factor of interest that could have been analyzed were number of Kanbans, processing time variations, demand variations, Kanban size, buffer and breakdown rate. Analyzing all the factors would be inefficient and time consuming, therefore, a 2^k factorial design is used for screening purpose (Hines, 1980). A 2^k design is particularly useful in the early stages of experimental research especially when there are likely to be many factors to be investigated. Two levels are chosen for each factor and an assumption is made that the response is approximately linear over the range of the factor levels chosen.

Table 2

Levels of Control Variables for Screening Experiments

Factor	low	high
Number of Kanbans	1	3
Processing time variability	0.2	0.6
Demand variability	0.2	0.6
Kanban size	2	5
Buffer	depends upon Kanban size and # of Kanban	60 units
Breakdown rate	0	4

Since, there were 6 factors, the 2^6 full factorial design with one replication was run to screen the main variables. Two and higher order interactions were assumed negligible. It was found that the main effects of Kanban size, and buffer were not significant.

Independent Variables

Number of Kanbans (n). This is an important parameter in the study. Queue capacity for any stage depends upon the number of Kanban allowed for that stage. Limiting queue capacity causes blocking and back-order. Simulation data are collected and analyzed for three levels of Kanbans (1, 3, and 5).

Processing Time Variability (Cvp). The machine processing time is the key variable in the study. The processing times for all the machines are assumed to be normally distributed.

Truncated normal distributions were used for cases with high variances to avoid the cases of negative processing. These truncated distributions are statistically acceptable (Sarker and Fitzsimmons, 1989), but may not represent the actual distribution in the case of large truncation. The highest coefficient of variation (Cov) used was 0.6, For which, 4.5% of the random numbers would be negative. Negative numbers were discarded and a new random samples were taken from the truncated distribution.

Normal processing time was chosen because in our study, variability is of prime importance and it can be represented very easily by using normal distribution. The mean processing time was assumed to be between 1.5 and 3 time units. Four levels of variability are considered: low (Cvp=0), medium (Cvp=0.2), medium high (Cvp=0.4) and high (Cvp=0.6). The processing times are varied to simulate the effects of different levels of product or process variation. Product variation can be the result of a range of sizes or of customizing features required. Process variation can be caused by variances in machines, tooling, operators, materials and yields.

<u>Demand Variability (Cvo).</u> Orders arrived randomly at the final stage and were released to the shop floor in the order they arrived to the production system. The time between order arrival and quantity per order are normally distributed. Four levels of demand variability were considered (Cvo = 0, 0.2, 0.4, 0.6).

Machine Breakdown. Each workcenter is assumed to have a limited production capacity. In addition, each workcenter has its availability characteristics, determined by the reliability of the machines. Both of these factors have the effect of constraining the output from each machining center. For experimental purposes, we modeled reliability by specifying the breakdown frequency of each work center. The time between machine failure was normally distributed and repair time was exponentially distributed. The mean time between arrival of breakdown was assumed to be very high compared to the processing time. Three levels of breakdown are considered, namely, 0, 4 and 8 breakdowns per run.

Verification

The developed model was verified in two major steps. First, the coding was thoroughly checked for correctness. The code was developed in modules and each module was tested separately for its execution. As each new module was added, it was tested against several small data sets simple enough to compare the simulation results against manual calculations and intuition. A simple manufacturing environment was constructed having only one end product and no disturbances. After simulating this environment, the actual inventory levels, utilization, and throughput are compared to those manually calculated. Results were found in close proximity.

Validation

Initial Conditions

At the beginning of each run, all queues were cleared and each station was idle. At the start of the run, Kanbans were introduced into the system. Event 1 initiates the processing at the first time unit. Each run had a length of 10,000 time units.

Steady State

Concept of steady state is subjective in nature. It is a limiting condition which is approached, but never actually attained. This means that there is no single point in the simulation beyond which the system is in steady state. Conway (Conway, 1962) defined the technique for determining equilibrium. Measurements were collected after every 500 time units. After each replication, any of the collected statistics can then be plotted as a function of time to give an indication of the behavior of the system. Conway's technique is to ignore all measurements until a measurement is neither a maximum nor a minimum of the ignored set. This ignored set of measurements is then used as the standard set of measurements which is deleted from the collected data. In the simulation study, steady state was found to occur after 2000 time units; so statistics were collected after 2000 time units.

Ending Conditions

The model was tested under various operation conditions, and it accurately replicated the operations of the example production system.

Performance Measures

Profit

Although the Japanese philosophy inherent in the JIT system emphasizes the minimization of inventory, it may be prudent to consider profits more prominently. There may be some penalty associated with a philosophy that focuses on inventory reduction without a least glance at the cost implications. In this simulation analysis, the primary measure of system performance is the total profit computed as the algebraic sum of the total revenue, WIP cost, back-order, overtime and setup costs. The backorder cost per back-order is twenty times the holding cost.

Backorder

Back-order has some cost associated with it. The implication is that expediting, overtime, or subcontracting is occurring, or perhaps the process is running at a faster than optimal speed. There may also be the cost of idle labor at subsequent work-centers which are waiting for the product. Every back-order has a fixed cost associated with it.

Production Lead Time

Production lead times in a multi-process factory consist mainly of waiting time, conveyance time, set-up time and processing time. Two components have been considered for the time spent waiting until production can begin: (1) time waiting for raw material or parts (if available) and (2) time waiting for processing resources to become available. While in reality these two component times can overlap, the assumption that will be made in this paper is that the lot will not be available for production until all necessary parts or raw materials are available. Once they are available, the lot will then start to wait for processing. Further, it is assumed that the raw materials or parts are withdrawn from inventory as soon as the Kanban starts to wait for processing (rather than waiting until lot processing actually begins).

Machine Utilization

It indirectly indicates the load on the system. It is a function of queue capacity and processing time distribution. Very low machine utilization indicates the investment loss and very high utilization indicates a high probability for machine breakdown. Optimal Figure for the utilization in a JIT controlled line is thought to be in the range of 0.5 - 0.7.

Material Processing Lead Time

It indicates mobility of the system in terms of material movement and reflects system flexibility so as to adapt to different products. Reduced set-up time and processing time have been assumed because large set-up and processing time results in large material processing time which, in effect, causes the inflexibility in the system.

CHAPTER IV

RESULTS, ANALYSIS, AND DISCUSSION

The preceding chapter described a 4-stage, subcell linked, pull-controlled model. This chapter discusses and analyzes the results obtained from the simulation run. To study the effect of each factor, a set of one-at-a-time experiments were performed. The impact of each factor is individually assessed by changing its setting from low to high, holding all other factors at their standard values. The model was run on an IBM mainframe. CPU time ranged from 45 seconds to 2 minutes depending upon the variance of the stochastic processes. The system parameters which have been considered in the model are given in Tables 3 to 6.

Table 3

Service Time Distribution for Main-Line Stages

		Service Time Distributions*		
Main line Stations	Number of servers	Type A	Type B	Type C
WS1	1	N(2.5,V)**	N(1.5,V)	N(2.1,V)
WS2	1	N(2.0,V)	N(2.25,V)	N(1.75,V)
WS3	1	N(2.0,V)	N(2.5,V)	N(1.5,V)

* at WS, the service time is for single stage
** N(2.5,V) means normal distn. with mean 2.5 and variable (V) std. deviation

Table 4

Service Time Distribution for Subcell Machines

Subcell Machines	Number of Machines	Service Time distributions: Type A	Type B	Type C
MC11	1	N(1.5,V)	N(1.5,V)	-
MC12	1	-	N(1.2,V)	N(1.2,V)
MC13	1	N(1.3,V)	N(1.3,V)	-
MC14	1	N(1.35,V)	N(1.35,V)	
MC21	1	N(1.8,V)	-	N(1.8,V)
MC22	1	N(1.6,V)	N(1.6,V)	-
MC23	1	N(1.7,V)	N(1.7,V)	N(1.7,V)
MC31	1	-	-	N(2.0,V)
MC32	1	N(1.65,V)	N(1.65,V)	N(1.65,V)
MC33	1	N(0.7,V)	N(0.7,V)	N(0.7,V)

Table 5

Cost Data Used in the Study

Revenue from a order	$900 / order
Capital equivalent loss for order balking	$450 / order balked
Backorder Cost	$200 / backorder
Cumulative Overtime	$2 / time unit
Set-up Cost	$1.75 / setup
Work-In-Process	$10 / unit of WIP

Table 6

Input Parameters Used in Study

Size of the Container	2 units
Quantity / Order (Units)	N(15,3)
Demand inter-arrival time distn.	N(57,V)
Set up time	1.5 time units
Order due date	375 time unit
Threshold order waiting time	249 time unit
ML stages' maintenance distn.	N(90,V)
Subcell machines' maintn. distn.	N(90,V)

The values, which were assumed in the experiments, were determined after refering to many articles which had discussed JIT system. Order due date and threshold order waiting time were fixed in such a fashion that a little change in processing time variation, demand variation, and breakdown rate would amplify its effect on the system. The service time of all the machines were considered small numbers because JIT system works well in this kind of arrangement. Cost data were in accordance with the analysis done by Huang, LOren, Rees and Taylor (1983).

There are a few terms which need to be explained before proceeding further into results analysis. An order not processed by the due date is considered a backorder, and amount of time taken past the due date by that order to get completely processed is considered overtime. The summation of overtime for all the backorders over one simulation run is defined as 'Cumulative overtime'. Threshold order waiting time is the maximum time which an order can wait for its turn to get processed. Any order that waits longer than the threshold order waiting time leaves the system. This process is known as 'balking'. The percentage of the time the main-line work-station waited for the material from the subcell is defined as 'Dependence Coefficient' (DnC). This coefficient is used to study the effect of subcells on the main line.

The data from the 3 replications of each simulation run were collected and analyzed. The mean and the standard deviation were calculated for most of the performance measures. The effects of variability and the number of Kanbans on the system performance measures were analyzed. The 'best' line configuration (in terms of number of Kanbans, lot size, setup, scheduling rules, withdrawal cycle time, etc.) for known environmental settings (Cvp, Cvo) could have possibly be chosen based on the performance measures discussed in the third chapter; but these configuration parameters are controlled by the management and changing these variables would not reflect the inherent variability present in the system. Moreover, The main purpose of this study was to analyze the effects of variability and the number of Kanbans on the system.

The results of the experimentation with the model are divided into four categories: (1) the effect of the number of Kanbans, (2) the effect of processing time variability, (3) the effect of demand variability, and (4) the effect of breakdown rate. Results were found to be consistent at every breakdown rate. For the purpose of discussion, the results with no breakdown rate have been shown here.

The Effect of the Number of Kanbans

Kanbans have a pronounced effect on the system performance. The number of Kanbans establishes the maximum inventory allowed and provides the flexibility to process more jobs in case of an increase in demand. In some cases, the system may concomitantly have enough production capacity to meet the increase in demand and yet production may be bounded by a relatively small number of Kanbans allowed in the system. Simulation results show that fewer Kanbans in the system makes performance more sensitive to variation and changes because having fewer Kanbans puts more constraints on the system, and reduces flexibility.

This section can be further broken down into three subcategories. The first subcategory analyzes the effect of varying Kanbans in Main line (ML) only (Main effect); the second sub-category analyses the effect of varying Kanbans in subcells only (subcell effect); and the third subcategory discusses the influence of the final stage Kanban number (final stage effect).

Main Effect

Throughput

The throughput of a pull system is a result of the WIP configuration and WIP is a linear function of a number of Kanbans. Throughput, WIP, and the number of Kanbans are therefore, strongly interrelated. As shown in Figure 12, an increase in the number of Kanbans increases the throughput. This is due to the fact that it creates an artificial demand and reduces the opportunities for blocking. The rate of increase in throughput is greater at lower Kanban levels than the one at higher Kanban levels because throughput is limited by the number of Kanbans. At high enough Kanban levels, throughput is bounded either by the demand requirements or by the system capacity. Increasing Kanbans beyond this point only results in WIP accumulation with the same output. Figure A in the appendix shows that this behavior is observed for all the coefficient of variations and is more dramatic for distributions with a higher degree of variability. This suggests that a reduction in the average WIP as a means of identifying problems may not always be effective (except where WIP is excessive) and would not result in success unless variability and process complexity are also reduced.

Backorder and Cumulative overtime

Variances in cumulative overtime and orders balked from the system reflect the amount of instability the production

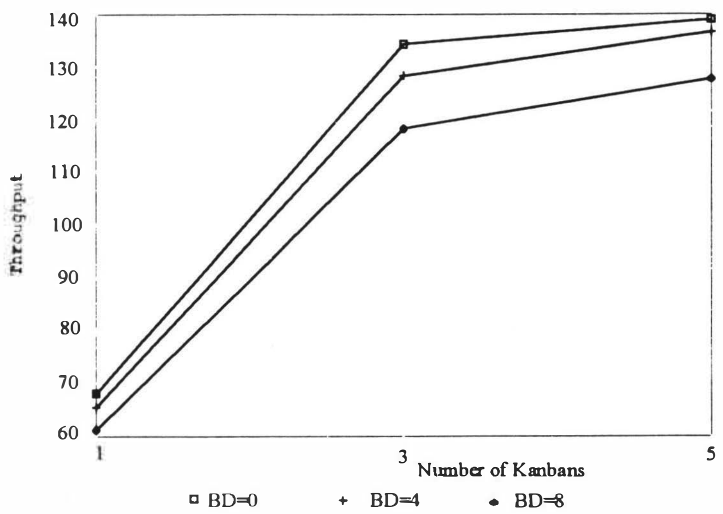

Figure 12. Effect of Number of Kanbans on Throughput at Varying Breakdown Rate.

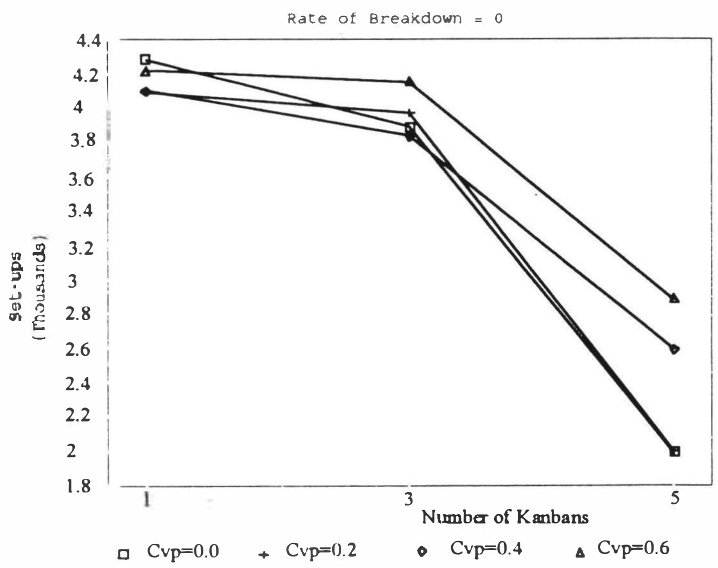

Figure 13. Effect of Number of Kanbans on Set-ups at Varying Processing Time Variability.

system has to face. As the number of Kanbans in each loop is decreased, the system reaches the maximum throughput level, where demand can no longer be met. This increases the mean and the variance of the number of orders balked, cumulative overtime, and backorders. From Table 7, it can be seen that as the number of Kanbans increases from 1 to 3, the buffer drastically reduces cumulative overtime and the number of orders balked from the system.

Table 7

Variation of Overtime and Order Balked With Number of Kanbans, BD = 0, Cvo = 0.6, Cvp = 0.6

	Cumulative Overtime		Orders Balked	
Number of Kanbans	Mean	Std. Dev.	Mean	Std. Dev.
1	5241.4	542.9	72.31	7.01
3	232.9	204.2	8.2	5.30

Further increases in the number of Kanbans has only passable effect. Also, as the number of Kanbans increases, the mean and the variance of cumulative overtime decreases because excess Kanbans act as a buffer and backordered demands can be met from excess capacity.

Set-ups

From Figure 13, it can be seen that as the number of

Kanbans increases, the number of setups decrease. This is because of the increased probability of the same type of Kanbans (containers) getting processed back to back. Surprisingly, the number of setups at the Kanban levels 1 and 3 are approximately the same. This is due to the opposing effect of the increase in throughput with the increase in number of Kanbans. Increase in throughput results in more number of completed orders of each kind, which in turn results in more setups.

Profit

The above subsections describe the behavior of every component of profit with respect to the number of Kanbans. Figure 14 graphically illustrates that behavior. As depicted in Figure 14 and Figure 15, profit increases with the number of Kanbans. At a higher levels of Kanbans, increase in profit is marginal because increase in throughput is marginal and the increase in WIP cost is nullified by the reduction in setup costs. This same model can be used to find the optimum profit; to optimize profit, one would choose the number of Kanbans at which marginal revenue equals marginal cost.

Production Lead Time and WIP

Figure 16 shows that production lead time (TISOO) decreases with an increase in the number of Kanbans. TISOO is high at lower levels of Kanbans because most jobs will wait for Kanban acquisition. On the other hand, at higher Kanban levels, containers

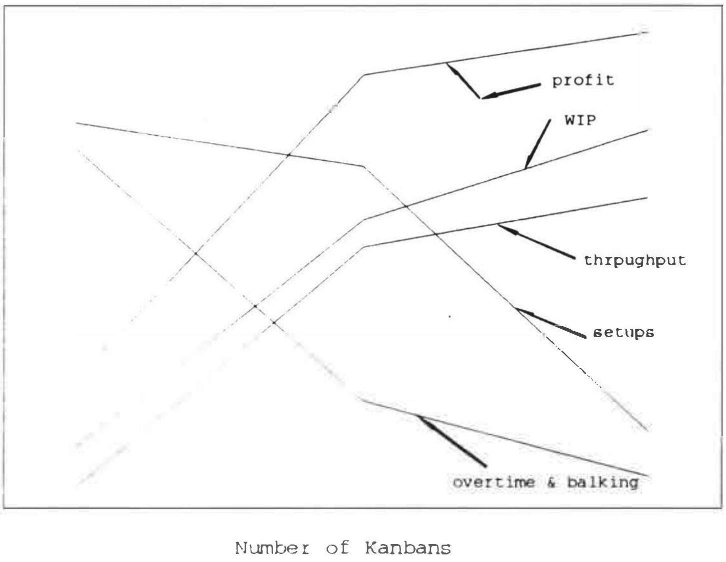

Figure 14. Performance Characteristics of Pull-controlled System as a Function of Number of Kanbans.

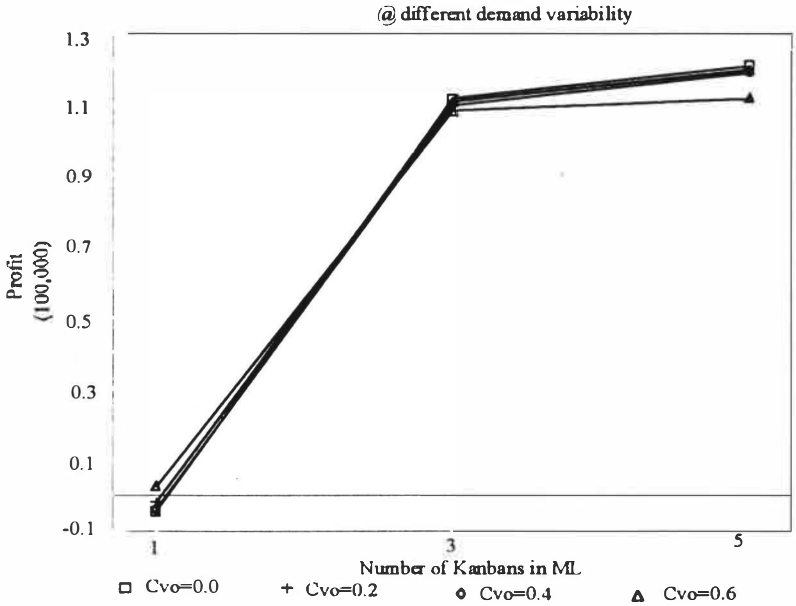

Figure 15. Profit as a Function of the Number of Kanbans.

will become available right away and this will decrease TISOO. Production lead time variability implies uncertainty in the system that adversely effects the serviceability aspects of the industry. An increase in number of Kanbans lowers this variability as displayed in Table 8.

Table 8

Effect of Number of Kanbans on Production Lead Time Variability

Number of Kanbans	Std. dev. of TISOO
1	119.67
3	76.2
5	59.78

A lower number of Kanbans lets fewer jobs enter the system and thus results in lower WIP. Hence, the number of Kanbans has an opposite effect on the WIP and production lead time. Figure 17 shows the tradeoff between the WIP level and production lead time. These results are expected to be helpful for the companies in fixing an optimum service level for their customers.

Material Lead Time (TISOM)

TISOM increases with the number of Kanbans because a greater number of Kanbans decreases the probability of emptying

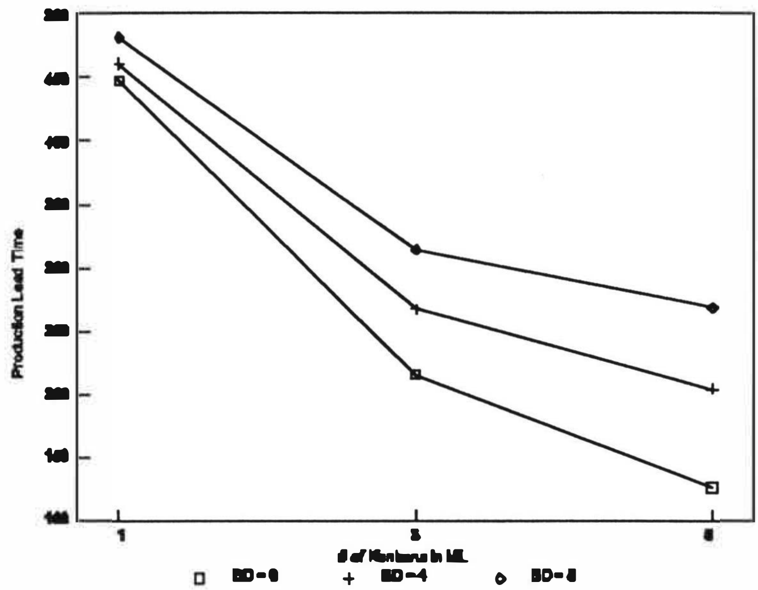

Figure 16. Effect of Number of Kanbans on Production Lead Time at Different Breakdown Rate.

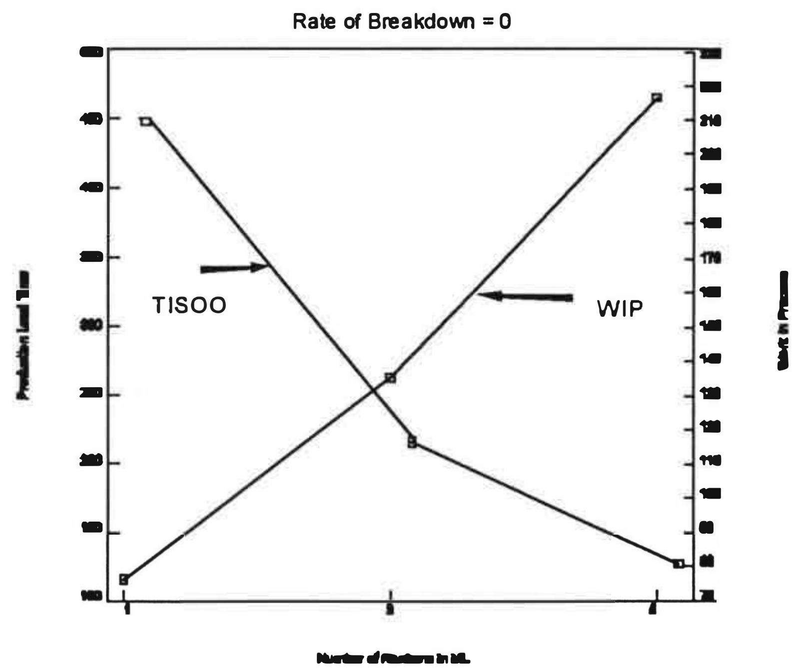

Figure 17. Comparing Production Lead Time and WIP.

a container produced at a successor workcenter. Moreover, the random mixture of products makes this behavior highly stochastic. A high number of Kanbans and high demand variabilities have adverse effect on the material lead time as is evident in Figure 18.

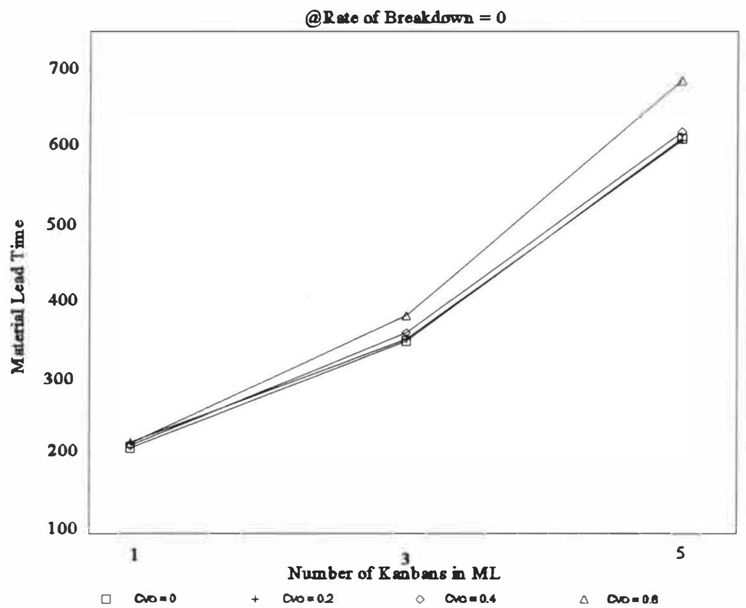

Figure 18. Effect of Number of Kanbans on Material Lead Time at Different Demand Variability.

Utilization

Machine utilization increases almost exponentially with an increase in the number of Kanbans. An increase in the number of Kanbans increases the throughput of the system and hence the utilization. Machine utilization increases almost 65% when the number of Kanbans is increased from 1 to 3. However, the increase was approximately 4% when the number of Kanbans was increased from 3 to 5. In the latter case, utilization was limited by the system capacity. Any subsequent increase in the Kanban number would not make any remarkable change in the machine utilization (refer Table 9).

Table 9

Variation of Utilization and Dependence Coefficient With Number of Kanbans

Number of Kanbans	Utilization	Dependence
1	0.367	0.00
3	0.617	0.133

If capacity had been unlimited, a greater number of Kanbans would have led to high throughput and hence higher utilization. As the utilization of the machines increases, the probability of backorders and overtime increases, which in turn deteriorates the system performance. Therefore, in JIT systems, utilization is almost always kept between 50% and 70% (Monden, 1981).

<u>Dependence Coefficient (DnC)</u>

When the number of Kanbans in the ML is reduced to 1, DnC drops to zero because a lower number of Kanbans in the ML results in subcells having extra capacity as compared to the ML; this makes the ML virtually independent of the subcells(see Table 9). An increase in the number of Kanbans increases throughput and utilization; this puts more demand on the subcells, increasing the dependence coefficient. Increase in the number of Kanbans from 1 to 3, increases the DnC substantially, however, increase was marginal when the number of Kanbans increases from 3 to 5.

Statistical Results

To check the significance of each of the performance measures, general principles of experimental design were used (Hines, 1980). The design was assumed to completely randomized. We are concerned with testing the hypothesis that the means of the observations at different levels of Kanban number are equal. It is also assumed that we are dealing with normal populations with equal variances. The statistical method presented is fairly robust; that is, it is relatively insensitive to violations of the assumption of normality as well as the assumption of equal variances.

The model equation for the one-way classification can be written as

$$Y_{ij} = \mu + \alpha_i + e_{ij} \quad for\ i=1,2,...,k; j=1,2,...,n$$

where μ = grand population mean

k = level of number of Kanbans, and

n = replications

Null Hypothesis: $H_o: \alpha_1 = \alpha_2 = \alpha_3$

Alternate Hypothesis: $H_a: \alpha_i \neq$ for some i

The sample calculation (ANOVA Table) and the table of significance is shown in the Appendix. It was found that all the performance measure were significant at significance level (SL) of 10% implying the rejection of null hypothesis and significance of the effect of Kanban.

Subcell Effect

This subcategory compares the effect of change in Kanban in SC with the effect of change in Kanban in ML. Figure G to Figure K in the appendix graphically demonstrate the behavior. Throughput increases with the number of Kanbans in SC, but an increase in the number of Kanbans in the ML has more dominant effect on throughput compared to that of SCs. For example, an increase in ML Kanbans from 3 to 5 increases throughput by 8 orders, whereas, an increase in the number of Kanbans in SC from 2 to 4 increases throughput by merely 3 orders.

Compared to the ML, an increase in the number of Kanbans in SC has an opposite effect on cumulative overtime and the number of setups. Increase in the number of Kanbans in SC, considerably increases overtime, number of setups, and WIP, which results in decrease in profit. Thus, it indicates that increasing the number of Kanbans above the optimum level has detrimental effect on the system performance and emphasizes the need to judiciously choose the number of Kanbans.

The utilization of the manufacturing subcell increases with an increase in the number of Kanbans in subcell. The under-utilization of the subcell machines with fewer Kanbans is due to the lower production level; this causes the delayed delivery of the full containers from the subcells to the main-line. This results in a high value of DnC. As the Kanbans are increased in a subcell, DnC approaches zero. This means that an increase in the number of Kanbans in SC makes the ML independent of SC, but at the cost of very high WIP. Fewer Kanbans in subcells (SC) makes the ML stages starve for the material; an increase in the number of Kanbans in SCs, to some extent, takes care of starvation as depicted by DnC. This increases the material turnover rate and hence reduces the material lead time (TISOM). Results suggests that further increase in the number of Kanbans in SC increases the TISOM. Increase in number of Kanbans in SC does not have any significant effect on the production lead time.

Final Stage Effect

The results obtained for the Kanban/pull are shown in Figure L to Figure P in the appendix. Figures illustrate that reducing the number of Kanbans in the final stage has a more severe impact on system performance than a reduction in the early stages. As the number of containers in the final stage increases, cumulative overtime decreases dramatically. Contrarily, increasing the number of Kanbans in preceding stages does reduce cumulative overtime but only slightly, because inventories at preceding stations cannot eliminate stock-out. External demand variability has a significant negative effect on the overtime and backorders, and as mentioned above, the last

Kanban loop has the largest impact on backorders. This reflects the important role of the downstream Kanban loop, in absorbing the external demand variance.

Increasing Kanbans at the final stage lowers inventory because available material at preceding stations is drawn to produce for final stage finished inventory. However, increasing the number of preceding stage Kanbans has the effect of increasing material availability to the final stage. This asymmetry in consequence exists simply because the preceding stages feed the final stage and the demand, which comes at final stage, is limited.

Variability in Processing Time[1]

Variability in the processing time has a very noticeable effect on system performance. When subsequent stages of the line are very closely linked and are highly dependent on each other (due to fewer Kanbans), the variability in processing time (Cvp) makes the behavior of the system very erratic and unstable. Processing time variation has more influence on profit, throughput, and other performance measure than demand

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1 This section and next section have an almost identical set of Figures. Most of the Figures are going to be in this section, but they can be easily applied to the succeeding section. Most of the Figures are drawn with respect to coefficient of variation of processing time at different demand variability.

variations because Cvp is an internal instability and demand variability is an instability external to the system. Cvp, therefore, has a direct impact on the system performance.

Effect of Cvp on Performance Measures

Throughput

Figure 19 shows the deterioration of throughput at a non-linear rate with Cvp. This result is due to the increase in probability of an empty queue with the variations. The expected production in a steady state is a negative function of the percentage of time a stage is idle, that is, it is

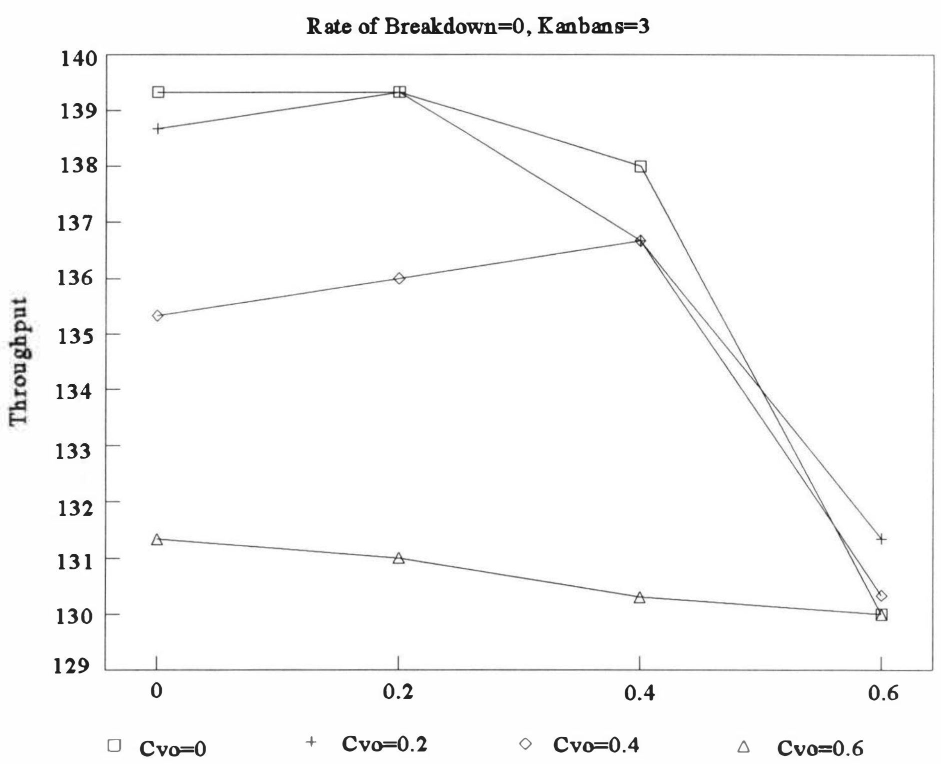


Figure 19. Effect of Variations on the Throughput.

inversely proportional to the percentage of time the queue is empty. Figure 19, also, compares the expected throughput of pull system at varying demand distributions. In circumstances where maintaining a high level of throughput is paramount and it is not possible to reduce variability, sufficient WIP inventories would compensate for the variability of process. Prior knowledge of this effect in a pull system is very useful to the operations manager in the sense that he can accordingly plan and schedule all activities ahead of time.

Cumulative Overtime and Orders Balked

As is evident from Table 10, cumulative overtime increases almost exponentially as the coefficient of variation of processing time increases.

Table 10

Alteration of Cumulative Overtime and Number of Orders Balked, BD = 0, Cvo = 0.2, Kanbans = 3

	Cumulative Overtime		Orders Balked	
Cvp	Mean	Std. dev.	Mean	Std.
0.0	3.83	5.42	1.67	1.4
0.2	28.10	23.15	2.77	2.3
0.4	46.26	44.36	4.00	2.5

For the production manager, this set of experimental results have several implications. First, if the workers are unable to reduce the variability in processing time (measured by Cvp) and, in fact, it increases, the mean overtime required will also increase, possibly to extremely high levels. For example, when 3 cards are present, an increase in Cvp by a factor of two increases the average overtime at least by a factor of two. Thus, the manager is confronted with a trade-off between overtime costs (which can also include nondollar worker attitude costs) and in-process inventory costs, since increasing the number of Kanbans reduces overtime. If management feels that the processing time cannot be standardized, then demand may not be met or excess inventories may result, thus defeating the purpose of a JIT system.

Variable processing time also results in large fluctuations in cumulative overtime. It can be seen in Table 10, variation in the cumulative overtime (as measured by the std. dev.) increases with Cvp. Overtime variability is amplified by the variability in processing time in the JIT system. The implication is that the manager who is trying to implement the JIT system must first prepare workers for large and varying amounts of work time and overtime. Also, increase in Cvp increases the number of order balked from the system exponentially. Orders balked represent the potential profit loss and market loss.

Set-ups

Effect of Cvp on the number of set-ups is not significant.

Higher number of Kanbans promotes higher relative change in the set-ups with an increase in Cvp. A change of Cvp from 0 to 0.6 increases the mean number of setups by 46% at Kanban level of 5. However, the same increase in Cvp, at Kanban level of 3, increases the mean number of setups by only 6%. This emphasizes the need to optimize the number of Kanbans in the system.

Work In Process

In a pull system, WIP is mostly controlled by the number of Kanbans but variability in processing time does have some marginal effect. The average inventory level or WIP slightly increases when Cvp increases. The WIP inventory starts building up slowly along the line as soon as the line starts experiencing an imbalance due to the variation of operation times.

Profit

Above subsections show the behavior of various components of profit; these results are graphically displayed in Figure 20. The interesting behavior of profit with the processing time variability is reflected in Figure 21; the behavior remains almost similar for every demand variability considered in the study.

A slight decrease in processing time affects profits tremendously. For example, decreasing processing time at station 1 and station 4 by 0.5 time units, increases profits from

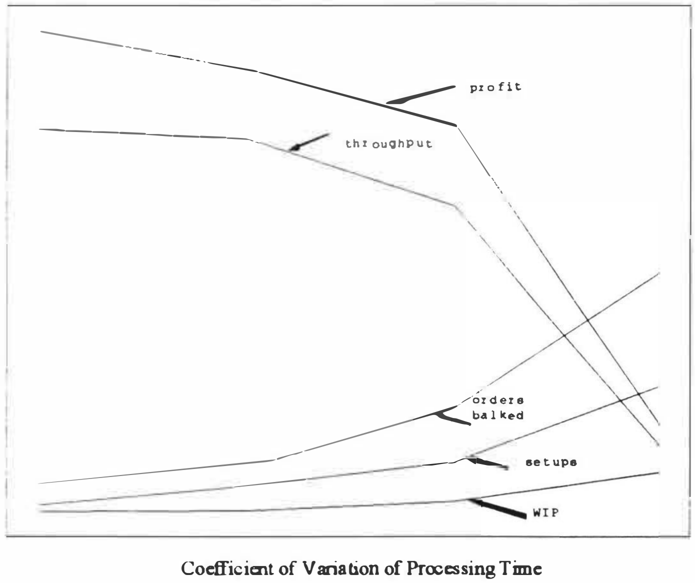


Figure 20. Performance Characteristics of Kanban-controlled System as a Function of Processing Time Variability.

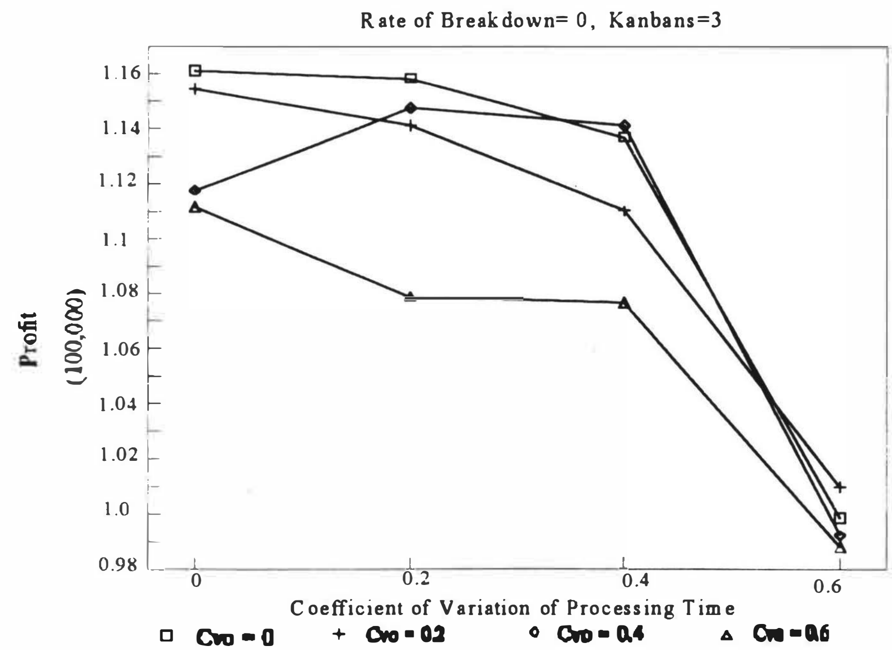


Figure 21. Effect of Variations on Profit.

$1,09,657 to $1,12,433. Other noticeable effects of decreasing the processing time at stage-1 and stage-4 are given in Table 11.

Table 11

Impacts on System Effectiveness with a Change in the Processing Times of 1^{st} and 4^{th} Stages

Performance Measures	percentage change
Set-ups	10 % increase
Work-In-Process	1.2 % decrease
Throughput	2.8 % increase
Production Lead Time	14 % decrease
Material Lead Time	9 % decrease
Utilization of 1^{st} and 4^{th} stage	20 % decrease
Dependence Coeff. of 4^{th} stage	18 % increase

Material Lead Time (TISOM)

Figure 19 and 22 indicate that throughput and TISOM behave in opposite manners with changes in Cvp. With the increase in Cvp, throughput decreases resulting in WIP accumulation; that results in a large TISOM. Implication is that high Cvp results in loss of flexibility in terms of customer demands.

Production Lead Time (TISOO)

Figure 23 indicates that as the Cvp increases, TISOO increases insignificantly. Slight increase in TISOO is due

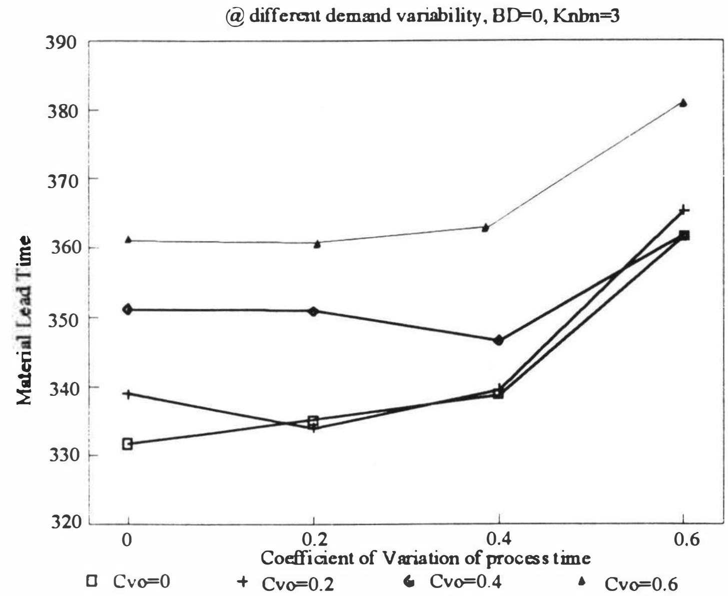


Figure 22. Effect of Processing Time on Material Lead Time.

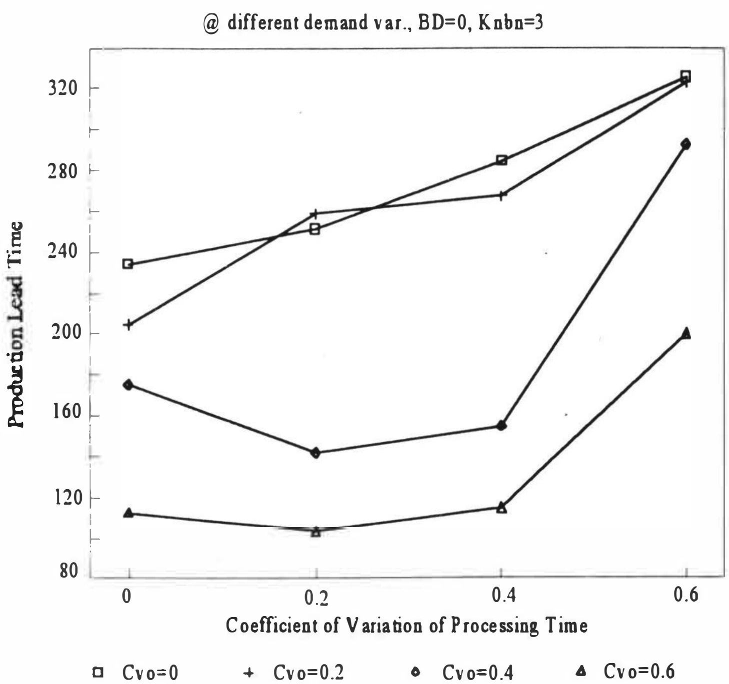


Figure 23. Effect of Processing Time Variability on Production Lead Time.

to the subcell performance deterioration. This instability results in an increase in the waiting time of ML material, thus resulting in slight change in TISOO. Also, an increase in processing time variability results in increase in lead time variability as shown in Table 12.

Table 12

Effect of Processing Time Variability on Production Lead Time Variability

Cvp	Std. dev. of TISOO
0.0	80.94
0.2	82.38
0.4	90.86
0.6	92.80

Utilization

Increase in Cvp results in marginal decrease of utilization. Increases in processing time variation cannot be offset by increasing the pull demand because raising the pull demand does not ensure a high process utilization. Process utilization is limited by the process capacity, number of Kanbans, and inherent variability in the system. If workers were tied up with a single process, there would be lot of under-utilized man power. That is why JIT encompasses labor mobility and multi-functional workers as essential components.

Dependence Coefficient

We observe in Figure 24 that the increase in Cvp increases the dependence of the ML on the subcell; i.e., ML material has to wait longer to get material from the subcells. This result is due to the fact that the performance of the ML, as well as the subcells, becomes erratic and unstable. This unreliability is reflected in the increase in the dependence coefficient.

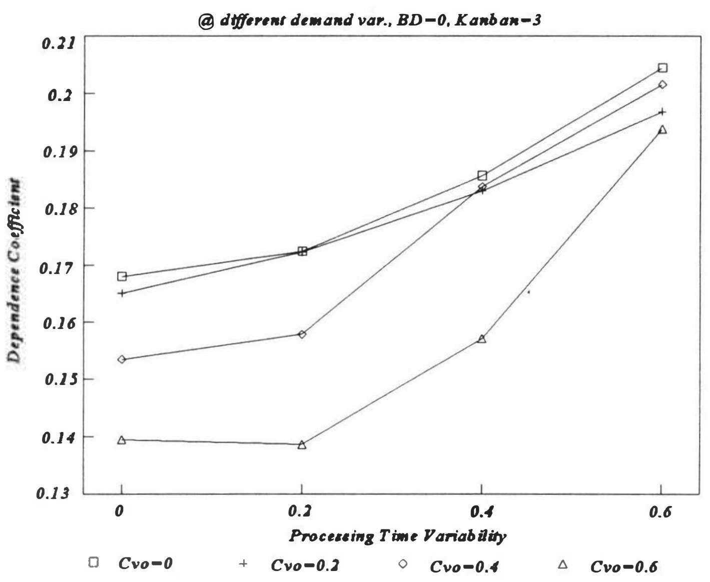


Figure 24. Effect of Variabilities on DnC.

Variability in the processing time reduces the production rate, increases shortages, and thus increases backorders and overtime. On the other hand, the production rate can be increased by increasing the inventory (via the number of Kanbans). This increased inventory acts as a buffer for the variability in the processing time. Therefore, to achieve the desired performance, a greater number of Kanbans are needed at high variability as compared to that at low variability.

Statistical Results

To check the significance of each of the performance measures, statistical analysis is performed. We are concerned with testing the hypothesis that the means of the observations at different levels of processing time variation are equal. The statistical method presented is fairly robust; that is, it is relatively insensitive to violations of the assumption of normality as well as the assumption of equal variances. The model equation and the hypothesis testing are the same as mentioned previously.

The sample calculation (ANOVA table) and the table of significance is shown in the Appendix. It is found that number of setups, WIP, production lead time, DnC, and utilization are not significant at SL of 10%. Which implies that Cvp does not have effect on the above mentioned performance measures. The above analysis proves that large variation in processing time has significant negative effect on the profit and material lead time.

Variability in Demand (Cvo)

Variability in demand (Cvo) can be due to either quantity variations, inter-arrival time variability, product mix variation, or any combination of these factors. In this study, however, variability due to only stochastic order inter-arrival time has been considered.

At lower levels of demand, when the line capacity is more relaxed, the production rate is found to be equal to the daily demand irrespective of the processing time variability or number of Kanbans. At very high levels of demands, when the line is overloaded, the production rate is found to be equal to or slightly less than the line capacity, regardless of any variability in the system. Hence, in determining the effects of the demand variability on the line performance, the demand level at which the line capacity is highly utilized is focused on.

Throughput

Figure 19 depicts that throughput (efficiency) decreases with demand variability because increases in Cvo increase system congestion and the probability of the system lacking orders. In a JIT system, the production line does not produce anything until it is asked for; this results in less throughput. Throughput decreases more rapidly at higher Cvo. A decrease in the throughput results in fewer setups. However, the decrease in the throughput results in fewer setups. However, the decrease in number of setups is marginal with respect to Cvo.

Work-In-Process

Demand variability has a slight impact on WIP. The WIP inventory at one stage is dependent upon how quickly the WIP inventory is passed through succeeding stages. System congestion at high Cvp obstructs the free flow of material and thus results in slight increase of WIP. This phenomenon is not very noticeable at lower Cvo but gets magnified with decreasing reliability.

Orders Balked and Cumulative Overtime

Cvo has a slight effect on the number of orders balked. With an increase in demand variability, system congestion and lower efficiency results in increased numbers of orders balking from the system.

Table 13

Impact of Demand Variability on Cumulative Overtime and the Number of Orders Balked, BD = 0, Kanbans = 3

	Cumulative Overtime		Orders Balked	
Cvo	Mean	Std. dev.	Mean	Std.
0.0	55.5	76.78	3.25	2.81
0.2	70.36	88.93	3.33	4.4
0.4	109.1	171.20	5.17	4.79
0.6	144.47	171.52	2.08	4.52

The results indicated in Table 13 shows that the mean and the variability of overtime increased significantly as the variability of the demand increased. Such large variations in overtime would cause problems for the production manager. To reduce the variation, the MPS must either be frozen or very nearly frozen.

Profit

When the various coefficient of variation of demand are substituted into the simulation model of the example shop, the total profit values shown in Figure 25 are generated. Notice that when the system has a sufficient number of Kanbans, variability has a deteriorating effect on profit and when the Kanban number is less than optimum, variability increases profits. This occurs because at insufficient number of Kanbans, high variability results in less overtime and less orders balking from the system (as shown in Figure B and Figure C in Appendix). The above subsections describe the behavior of all the cost components; from these description, it becomes very obvious that profit decreases with an increase in Cvo because an increase in Cvo results in reduced throughput, higher cumulative overtime and higher order balking. Figure 26 shows the same phenomenon.

Lead Time

Material lead time (TISOM) increases with Cvo (see Figure

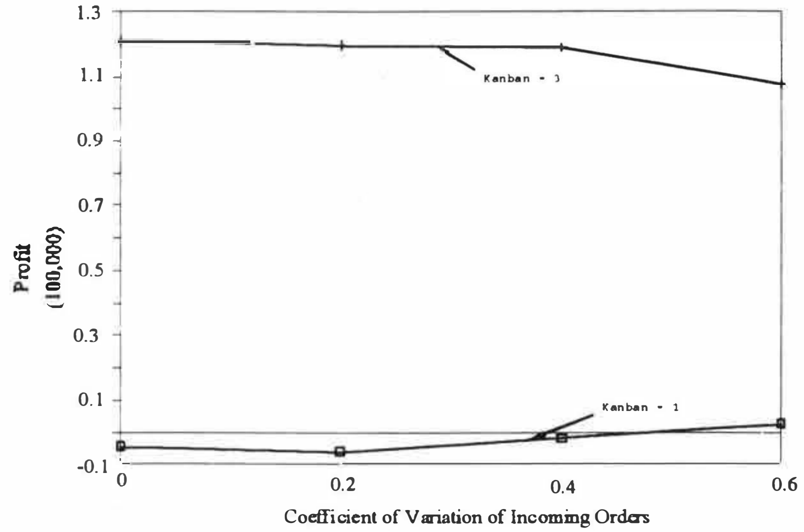


Figure 25. Effect of Demand Variability on Profit at Different Kanban Levels.

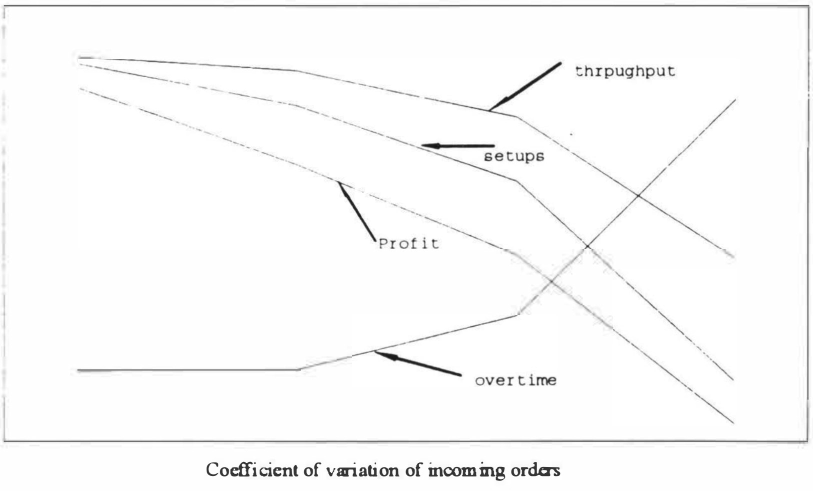


Figure 26. Performance Measures of a Kanban-controlled System as a Function of Demand Variation.

22); rate of increase is higher at higher variability. As mentioned before, with high Cvo, the probability of the system being without any ordersincreases; this results in an increased average stay of material and hence increased material lead time. Figure 23 shows that production lead time decreases with Cvo because orders are processed without much waiting for the material from the subcells (as manifested by dependence coefficient). Increase in Cvo affects the variability of TISOO significantly. As noticed in Table 14, increase of Cvo from 0 to 0.6 increases the variability of TISOO by approximately 125%.

Table 14

Effect of Demand Variability on TISOO Variability

Cvo	Std. dev. of TISOO
0.0	41.37
0.2	48.40
0.4	80.94
0.6	92.80

Utilization

Figure 27 compares the machine utilization at different processing time variability (Cvp). It indicates that machine utilization decreases drastically with an increase in Cvo at lower level of Cvp. At higher level of Cvp, however, increases in Cvo change the machine utilization slightly.

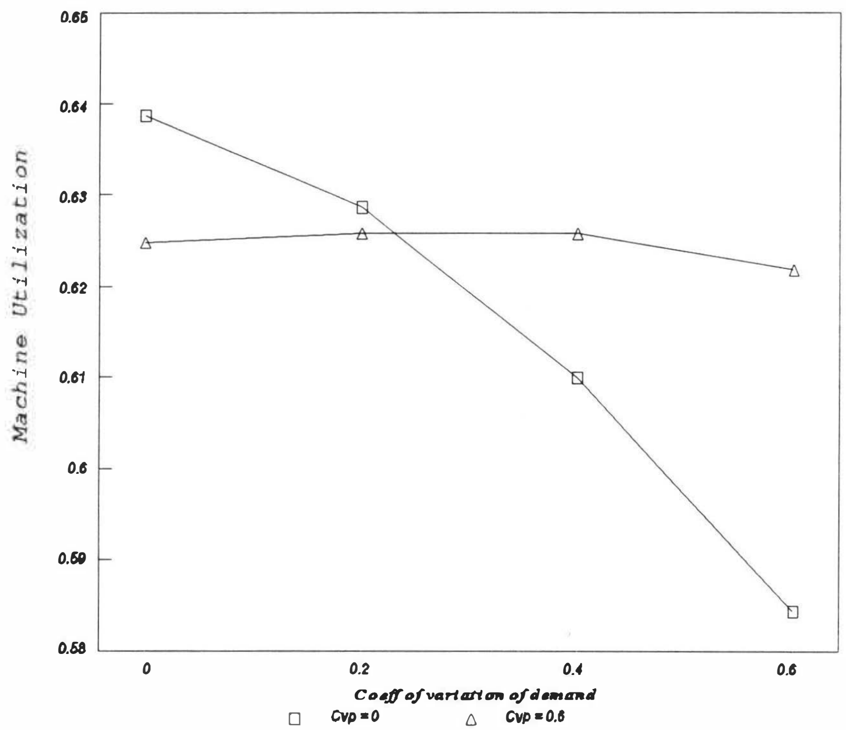


Figure 27. Effect of Variations on M/c Utilization.

Dependence Coefficient (DnC)

As the Cvo increases, subcell dependence vary insignificantly (refer Figure 24) because Cvo primarily affects the main line; it has little direct affect on the subcells. In other words, demand variability brings instability in the ML while subcells remain stable making subcell slightly efficient than main-line and thus reducing DnC.

As the number of Kanbans, and hence inventory, is reduced close to the feasible minimum, the system tends to be more sensitive to demand variability. This is because the reduction in the number of Kanbans brings the maximum system strength throughput close to the average demand, and that reduces the ability to quickly respond to demand variation. This seems to strengthen the practical observation that a steady demand is necessary benefit from a pull system (Huang et. al, 1983), although the effect of varying demand is reduced by increasing the number of Kanbans (and hence the total inventory).

Statistical Results

To check the significance of each of the performance measures, statistical analysis is performed. We are concerned with testing the hypothesis that the means of the observations at different levels of incoming orders variation are equal. The statistical method presented is fairly robust. The model equation and the hypothesis testing are the same as mentioned previously.

The sample calculation (ANOVA Table) and the table of significance is shown in the Appendix. It is found that cumulative overtime, number of orders balked, number of setups, and WIP are not significant at SL of 10%. Which implies that for the range of Cvo considered in the analysis; order balking, set-ups, and change is WIP do not occur significantly; though Cvo has significant negative effect on the cumulative overtime, profit, material lead time, production lead time and machine utilization.

Effect of Breakdown

A very few breakdowns, with short repair time, do not have a considerable influence on system performance provided enough of a buffer is present between the stations. However, the breakdowns with long repair times have a very detrimental effect on the system, irrespective of the buffer quantity present in the system. Machine breakdowns are considered only in the main-line and in subcell-1. Machines in subcell-2 and in subcell-3 are assumed to be reliable and their breakdown times are assumed to be negligible relative to the breakdown times in subcell-1 (SC-1).

This category is divided into two sub-categories, main effects and subcell effects. Main effects encompasses breakdowns in both the main-line and SC-1, whereas the subcell effects isolate variabilities due to the breakdown subcell only.

Main Effects

Throughput

As the mean number of breakdowns increases, throughput decreases non-linearly. Throughput decreased by 6.5 % when the mean number of breakdowns increased by 4 (from 0 to 4), but the same increase of 4 (from 4 to 8) decreases the throughput by 9 %. This implies as the machine reliability goes down, the performance of the system, in terms of throughput, profit, and utilization, starts deteriorating rapidly. This signifies the importance of preventive maintenance. Experimental data in Figure 28 suggests that at very low breakdown rates, variability has an adverse effect on the system throughput; at very high breakdown rate, however, the effect of variability on the system is suppressed.

Work-In-Process

It is apparent from Figure 29 that average WIP increases with breakdowns. The reason for this phenomenon is that the WIP at the stages preceding the broken stage continues to increase as production stoppage blocks material movement. An advantage of a Kanban controlled pull system is that WIP is bounded by the number of Kanbans and it does not continue to increase indefinitely. Once the system has been repaired or the cause of the stoppage has been rectified, WIP in all the stages goes back to the stable level as before the production stoppage.

Orders Balked and Cumulative Overtime

Machine breakdown has a very significant effect on the time required to complete an order. An increase in breakdown rate increases overtime and orders balked as shown in Table 15. The disruptive effects of equipment failures magnifies the negative effects of the temporary bottlenecks and component unavailability; this results in increased overtime and balking.

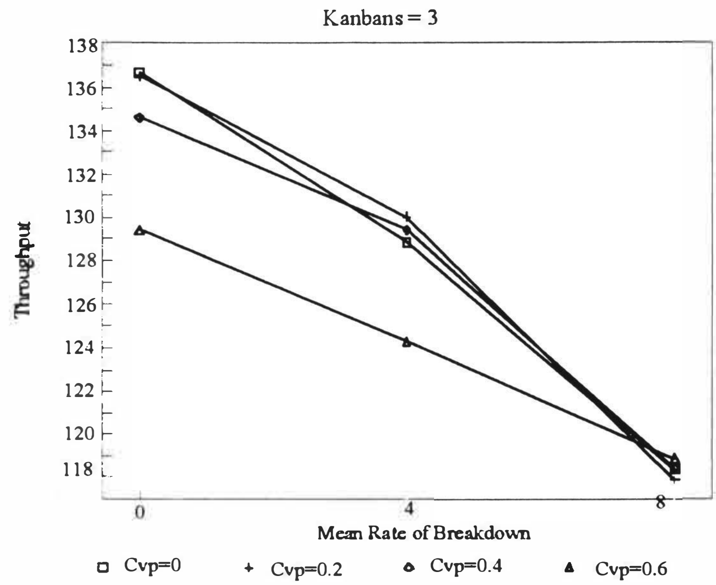


Figure 28. Effect of Breakdown on the Throughput.

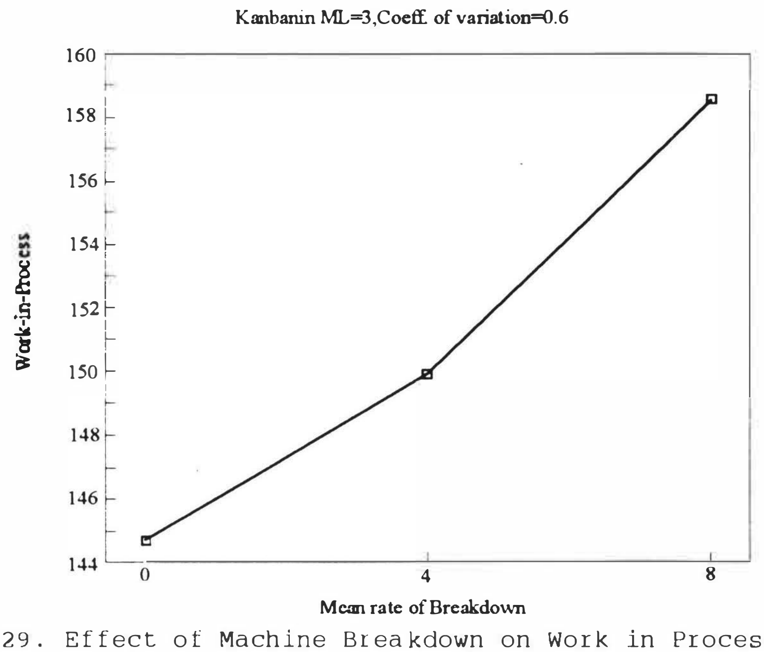


Figure 29. Effect of Machine Breakdown on Work in Process.

Table 15

Effect of Breakdown on Cumulative Overtime and Number of Orders Balked, Kanban = 3

	Cumulative Overtime		Orders Balked	
Mean rate of Breakdown	Mean	Std. dev.	Mean	Std. dev.
0	69.86	114.3	3.4	4.35
4	403.6	429.1	10.18	8.33

Profit

In this set of experiments, as reflected in Figure 30, where different components of profit are graphically displayed, we found that the mean profit of a pull system decreases non-linearly as the mean rate of breakdown increases. Figure 31 compares the mean profit earned. It indicates that as the mean number of breakdowns increases, the drop in the profit remains more or less constant for any number of Kanbans. The implication is that unreliability in system resources cannot be cushioned by adding more WIP.

Production Lead Time (TISOO)

Breakdowns do not have significant effect on TISOO. Breakdowns reduce the production rates of all the stages because the preceding stages do not produce anything that has not been

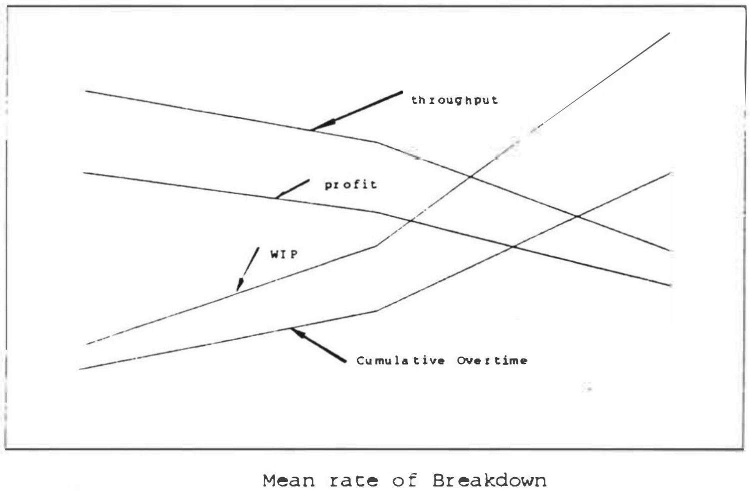


Figure 30. Performance Characteristics of a Kanban-controlled System as a Function of Breakdown.

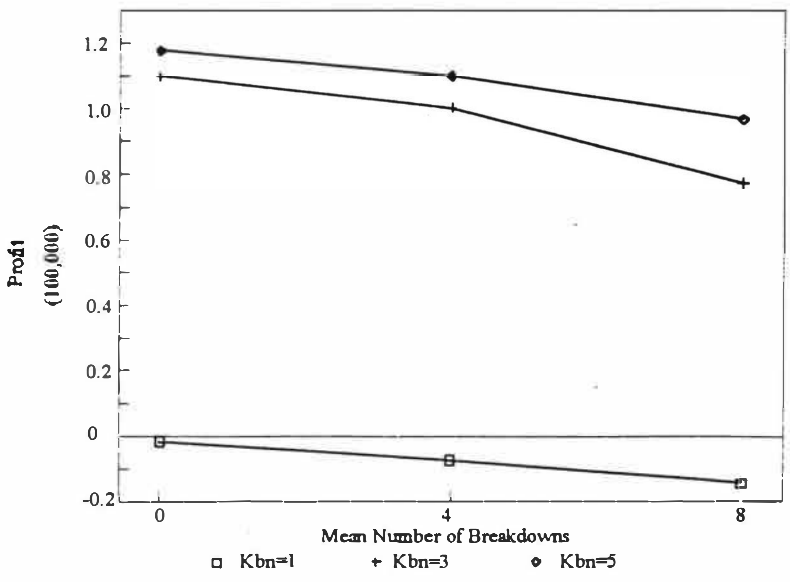


Figure 31. Profit Earned as a Function of the Breakdown Rate.

requested by the following stage. This production stoppage delays job processing and keeps orders waiting for material. Thus, there is a little delay in customer service. Increase in breakdown rate decreases the production lead time variability

Table 16

Effect of Breakdown Rate on Production Lead Time variability

Breakdown Rate	Std. dev. of TISOO
0	82.13
4	66.58
8	32.26

as shown in the Table 16. Reducing stoppages and breakdowns will reduce the lead time and bring the production of orders into close synchronization with the demand.

Material Lead Time (TISOM)

Breakdown has marginal effect on material lead time. Raw material is not drawn until requested by the first stage, which in turn will not place a request until demanded by the succeeding stages. On the other hand, the amount of material which is in the system and is waiting for the broke-down machine is a small fraction of the total quantity of material processed. These two factors result in marginal increase of mean material lead time over the simulation run.

Dependence Coefficient (DnC)

Table 17 shows that with breakdowns, the dependence coefficient increases, the rate of increase being greater at higher numbers of Kanbans. As seen in Figure F in appendix, with 5 Kanbans, an increase in the mean BD rate from 0 to 8 increases the DnC by 30%; whereas, with 3 Kanbans in the system, same increase in BD rate increases the DnC by 24%.

Utilization

Table 17 suggests that the decrease in machine utilization is not very significant with an increase in the mean breakdown rate. Moreover, the simulation results indicate that the relative utilization of a stage's facilities in a pull system with breakdowns is lower than in pull systems without breakdowns and is insensitive to the CoV and the number of Kanbans.

Table 17

Effect of the Breakdown on the Utilization and Dependence Coefficient

Mean rate of breakdown	Utilization	Dep. Coeff.@ Kanban=3	Dep. Coeff.@ Kanban=5
0	0.617	0.173	0.202
4	0.602	0.196	0.234
8	0.574	0.216	0.256

The numbers shown in Table 17 and analysis indicate that equipment failure does not influence performance significantly because we have considered small lot size and small setup times. Environments using small lot production, with small setup times, do not experience as much disruption from temporary bottlenecks and/or component unavailability.

Statistical Results

To check the significance of each of the performance measures, statistical analysis is performed. We are concerned with testing the hypothesis that the means of the observations at different levels of breakdown rate are equal. The statistical method presented is fairly robust. The model equation and the hypothesis testing are the same as mentioned previously.

The sample calculation (ANOVA Table) and the table of significance is shown in the Appendix. It is found that number of setups, production lead time, and material lead time are not significant at SL of 10%, which implies that for the range of breakdown rate considered in the analysis, lead times do not change significantly. Breakdown has significant negative effect on the throughput, overtime, WIP, profit and on the subcell dependence.

Subcell Effect

The following analysis encompasses the comparison of two situations: one in which the effects of breakdowns only in subsidiary cell are subjected to scrutiny, and another in which the effects of breakdowns only in main-line are closely examined. The results help us to distinguish the severity of the breakdowns between the two cases. The Figure U to Figure Z in appendix show a comparison of the impact of breakdowns in SC-1, breakdown in the ML, and breakdown in the system as a whole. Figures clearly reflect that breakdowns only in the ML have a more detrimental effect on the system performance than breakdowns only in the SC. This is due to the fact that subcell machine have low utilization and subcells follow push system, which inherently has better immune system against breakdown compared to pure pull system. Breakdowns only in the ML result in less throughput, more orders balking, more cumulative overtime, less profit, and greater production lead time compared to breakdowns only in SC-1.

Machine breakdowns in SC-1 dramatically increase the dependence coefficient pertaining to the first subcell. However, this makes other succeeding main-line stages less dependent on their corresponding subcells because a breakdown in SC-1 slows down the production; this provides other subcells with enough time to replenish their used-up inventories.

Results Validation

A 95% confidence interval was calculated for all the critical performance measures at 3 Kanbans, a mean breakdown rate of 8, and coefficient of variation of order and processing time equal to 1. Since the normal distribution with Cv of 1 would not represent a true normal distribution, the results were approximated using an exponential processing time and an exponential demand arrival time (Cvp=1 and Cvo=1). Table 18 shows the 95% confidence interval and the simulation results obtained at coefficient of variation of 1.

Table 18

Results Validation

		95% confidence interval	
Performance Measures	Simulation results	Lower	Upper
Cumulative Overtime	1669	1159.0	2825.7
Throughput	101	61	102
Order Balking	36	21.3	53.4
Profit	596.5	110.3	845.9
TISOO	288.3	171.6	298.7
Utilization	0.469	0.247	0.775

CHAPTER V

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In this research, the impact of variability in a JIT production system is discussed. This research has demonstrated what manufacturers without well-adapted and understood JIT factories can expect from their systems under variability and what preventive measures to take.

A methodology was developed to study Kanban-controlled pull system under dynamic environment. The methodology was unique in two ways. First, the main-line is interacting with subcells and second, main-line has pure pull configuration while subcell has pull scheme for withdrawing containers and push for manufacturing the containers. Advantage of proposed methodology is that the performance characteristics curves can be generated for most of the environmental settings.

A number of conclusions can be drawn from the results analysis:

1. An increase in the number of Kanbans results in increased throughput, decreased backorders and overtime, decreased order balking, reduced variability, swelled work-in-process, raised profit, reduced production lead time, and increased utilization. The change in the above mentioned performance measures is

not linearly proportional to the number of Kanbans. The change is dramatic up to a certain number of Kanbans; after this number is reached, change starts diminishing rapidly. That limit is a function of capacity, lot size, demand requirements, and components availability from the subcell.

2. For a given setting, reducing the number of Kanbans lower than the optimum would obviously have negative effect on the system. However, Kanbans can be decreased if variation is reduced by acquiring more effective machines, more effective production process and better trained workers.

3. There are a few advantages to lower variability in operation times which include: better output rate in a pull system, a reduction in overtime and order balking, a reduction in material lead times, a reduction in instability, and increase in utilization and profit.

4. Higher demand variability results in decreased throughput, increased cumulative overtime, decreased profit, increased material lead time, reduced production lead time, and a reduced machine utilization.

5. Demand variability has a distinctive effect at different number of Kanbans. At lower numbers of Kanbans, demand variability has a positive effect on profits due to the reduced cumulative overtime and fewer orders balked. At higher levels of Kanbans, demand variability has negative effect of profits.

6. The bearing of breakdown on the systems effectiveness is very noticeable. With an increase in the breakdown rate,

system efficiency and profits plunge rapidly. Also, breakdowns result in increased cumulative overtime, greater number of orders balking, raised production lead time, and increased dependence coefficient. Further, it has been noticed that breakdowns in the ML have more severe influence on the system compared to SC breakdowns because SC machines have a low utilization compared to ML machines. This indicates that SCs can even work with less reliable machines and with less frequent maintenance schedule.

It can be safely concluded from the above results that the Kanban system cannot conceal the negative consequences of a manufacturing environment (variability and breakdown) because the manufacturing environment has a greater impact on system performance than the type of shop floor control strategy used.

The results obtained in the previous chapter do not represent the universal behavior of all the systems. Results might vary from system to system depending upon the system's parameters and configuration. Nevertheless, the outcomes of the attempts are significant and provide fundamental insight into the system behavior.

Rest of the chapter emphasizes the concrete actions which can be taken to influence variability in the JIT systems.

The effects of demand variability can be controlled in five ways (Rees, 1987):(1) reducing lead times, (2) freezing MPS, (3) holding safety stocks, (4) smoothing of production in the final stage, and (5) using future demand information. The lead times can be reduced in many ways including process improvement, excess capacity, set-up time reduction and improved batching and sequencing. Frozen MPS and safety stock will provide a kind of buffer between the actual customer and the shop floor and will keep the production line aloof of any variation in demand. Smoothing of production in the final stage will minimize everyday fluctuations in the demand for various parts. In the pull system, the information flow is tied to the material flow; this results in a large information lead time. Using future demand information and transmitting demand information to the beginning of a series of operations would reduce the information lag time and the effects of demand variability.

Low processing time variability has a positive effect on the pull system as is evident from the results obtained, therefore, there is a need to minimize variability. To minimize variation in operation time, operations should be standardized and standard routines should be mastered. Variability reduced with time through learning curve effects. Hence, there is a necessity for establishing an appropriate time frame before the benefits of JIT system can be reaped.

In general, the ability to meet varying conditions and the flexibility to adjust to changing capacity requirement at a short notice must be maintained. For the companies which experience substantial variability in their demand and cannot freeze MPS, a JIT system will never be cost effective, regardless of the firm commitment to make it work.

Limitations and Caveats

1. Holding cost was assumed to be $10/unit of WIP/simulation run, which makes it $125/unit/year, based on 1 shift of 8 hour period. The practical value of holding cost is 20% - 40% of the product cost. Average product cost is $60/unit (order cost/average quantity per order). Taking 30% as holding cost, it came out to be $18/unit/year, which is equivalent to $1.5 per unit per simulation run.

The above explanation suggests that high holding cost has been assumed in the analysis. The effect of taking lower holding cost would be to increase the profit. Since the profit is in the order of 100,000s and the change in holding cost is in the order of 1,000s, the overall change in the profit would not be very significant.

2. The size of the container or Kanban size, as suggested by the literature, should be 5% to 10% of the daily demand. Average daily demand is approximately 120 units. That renders Kanban size to be in the range 6 to 12 units. In the analysis, two units per container have been assumed. In the screening experiments, Kanban size was found to be having no significant effect. That might quite possibly be due to the Kanban size chosen. Future research direction might be to study the effect of Kanban size on the system performance.

3. It was found that the variability in the results was high at high coefficient of variations, at high breakdown rate and at high Kanban number. The throughput for the system at Kanban number = 5, breakdown rate = 8 and processing time variability = 0.6 were studied from simulation results. Standard deviation of the data was found to be 5.643. The sample size can be calculated by the formula.

$$(t*std.dev.)^2/e$$

Assume error (e) to be 5 orders, and significance level to be 5%, sample size was estimated as 6. At confidence level of 10%, the sample size was estimated as 4. Results would have been more reliable, if sample size were taken as 6 replications instead of 3 replications.

Future Research Directions

In this research, the number of Kanbans at every stage is assumed to be the same. An increase in Kanbans means increasing the number of Kanbans in every stage. One of the future research directions would be to determine a better card configuration keeping in mind that it is better to add cards to the middle stage than to the extreme ones, provided service rates are approximately equal (Mitra and Mitrani, 1990).

Another future research possibility might be to study the same scenario with hybrid system (i.e. Kanban type pull system integrated with MRP type push system). Hybrid system will have the best of both the system, for eg. the smooth material flow capability of a JIT system and an excellent information flow system of a MRP system.

Some other possibilities might be to study the effect of buffer between the stations, the effect of interaction among the subcells, the influence of different policies for detaching WK (like detaching WK when last unit from the container is removed), and the influence of different practices for sending WK to the previous station for withdrawing material (like Fixed order withdrawal Kanban).

Appendix A

Statistical Results and Analysis of Variance Tables

STATISTICAL RESULTS FOR THE EFFECT OF NUMBER OF KANBANS
SIGNIFICANCE LEVEL = 10%

Performance Measure	Statistical Result
Throughput	Significant
Cumulative Overtime	Significant
Set-ups	Significant
Number of Orders Balked	Significant
W.I.P	Significant
Profit	Significant
Production Lead Time	Significant
Material Lead Time	Significant
Machine Utilization	Significant
Dependence Coefficient	Significant

Sample Calculations For the Throughput

Source of Error	Degree of Freedom	Sum of Square	Mean Square	F*
# of Kanbans	2	5439.06	2719.53	251.12
Error	33	357.83	10.83	
Total	35	5796.89		

$F^* = 2719.53/10.83 = 251.12$

$F_{(0.10,2,33)} = 2.32$

Since $F^* > F_{(0.10,2,33)}$, therefore we reject null hypothesis and conclude that effect of number of Kanbans on throughput is significant.

STATISTICAL RESULTS FOR THE EFFECT OF PROCESSING TIME VARIABILITY, SIGNIFICANCE LEVEL = 10%

Performance Measure	Statistical Result
Throughput	Significant
Cumulative Overtime	Significant
Set-ups	Not Significant
Number of Orders Balked	Significant
W.I.P	Not Significant
Profit	Significant
Production Lead Time	Not Significant
Material Lead Time	Significant
Machine Utilization	Not Significant
Dependence Coefficient	Significant

Sample Calculations For the Throughput

Source of Error	Degree of Freedom	Sum of Square	Mean Square	F*
Processing time Variability	3	60.44	20.148	12.089
Error	8	13.33	1.667	
Total	11	73.77		

F* = 20.148/1.667 = 12.089

$F_{(0.1,3,8)} = 2.07$

Since F* > $F_{(0.1,3,8)}$, therefore we reject null hypothesis and conclude that effect of Processing Time Variability on throughput is significant.

STATISTICAL RESULTS FOR THE EFFECT OF DEMAND VARIABILITY
SIGNIFICANCE LEVEL = 10%

Performance Measure	Statistical Result
Throughput	Significant
Cumulative Overtime	Significant
Set-ups	Not Significant
Number of Orders Balked	Not Significant
W.I.P	Not Significant
Profit	Significant
Production Lead Time	Significant
Material Lead Time	Significant
Machine Utilization	Significant
Dependence Coefficient	Not Significant

Sample Calculations For the Throughput

Source of Error	Degree of Freedom	Sum of Square	Mean Square	F*
Incoming Orders Variability	3	103.89	34.63	2.5
Error	44	609.5	13.85	
Total	47	713.39		

$F^* = 34.63/13.85 = 2.5$

$F_{(0.1,3,44)} = 1.87$

Since $F^* > F_{(0.10,3,44)}$, therefore we reject null hypothesis and conclude that effect of Demand Variability on throughput is significant.

STATISTICAL RESULTS FOR THE EFFECT OF BREAKDOWN RATE
SIGNIFICANCE LEVEL = 10%

Performance Measure	Statistical Result
Throughput	Significant
Cumulative Overtime	Significant
Set-ups	Not Significant
Number of Orders Balked	Significant
W.I.P	Significant
Profit	Significant
Production Lead Time	Not Significant
Material Lead Time	Not Significant
Machine Utilization	Not Significant
Dependence Coefficient	Significant

Sample Calculations For the Throughput

Source of Error	Degree of Freedom	Sum of Square	Mean Square	F*
Breakdown Rate	2	83.2	41.6	1.8
Error	141	3260.29	23.12	
Total	143	3343.49		

$F^* = 41.6/23.12 = 1.8$

$F_{(0.1,2,141)} = 1.66$

Since $F^* > F_{(0.1,2,141)}$, therefore we reject null hypothesis and conclude that effect of breakdown rate on throughput is significant.

Appendix B

Figures

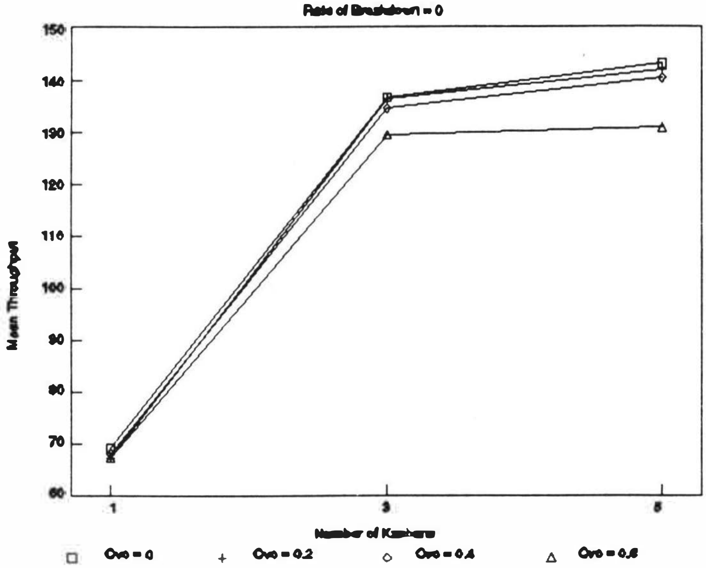


Figure a: Effect of number of Kanbans on throughput at varying demand variability

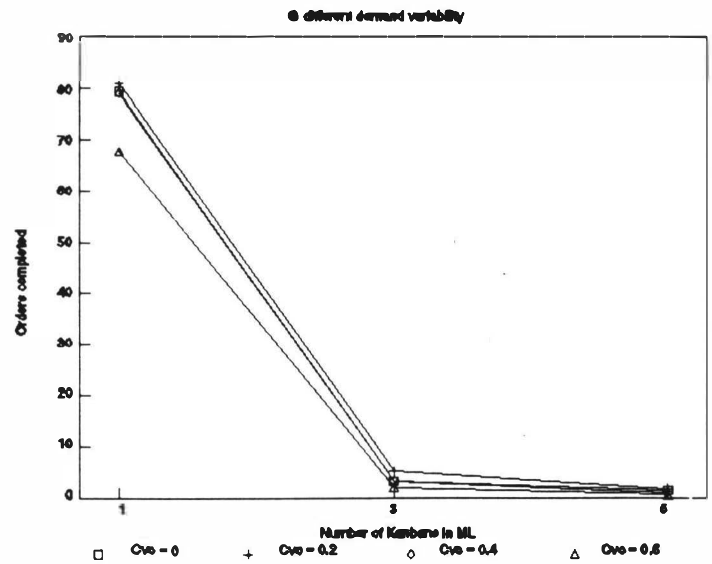


Figure b: Number of orders balked as a function of number of Kanbans

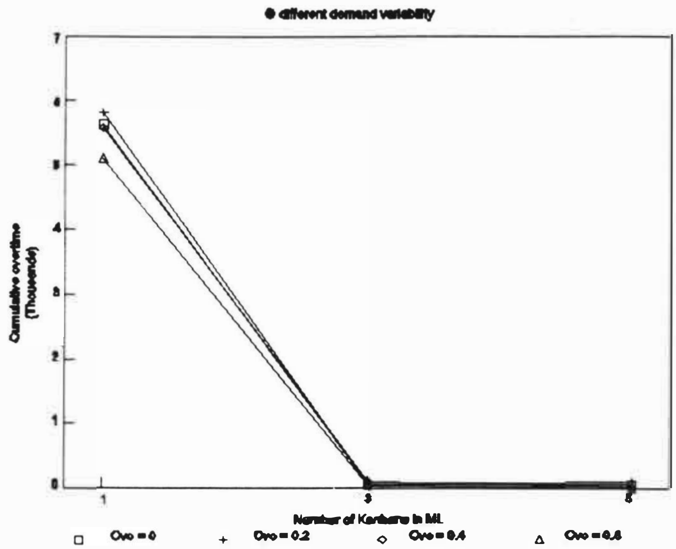


Figure c: Cumulative Overtime as a function of the number of Kaanbans

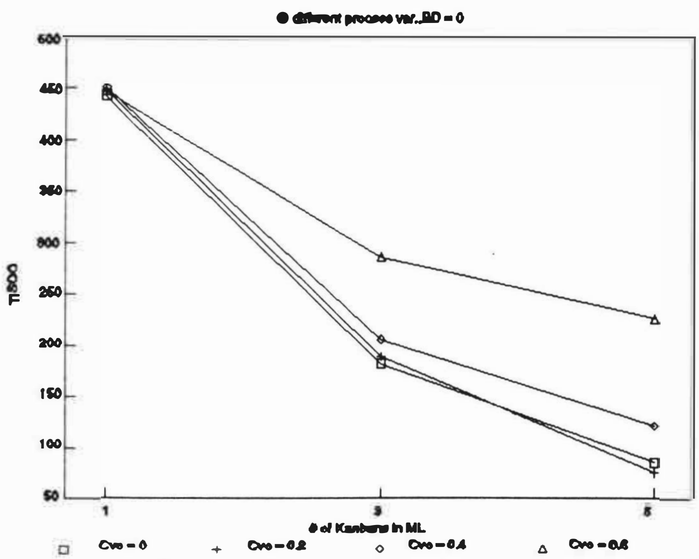


Figure d: Production lead time as a functionof the number of Kanbans at different demand variability

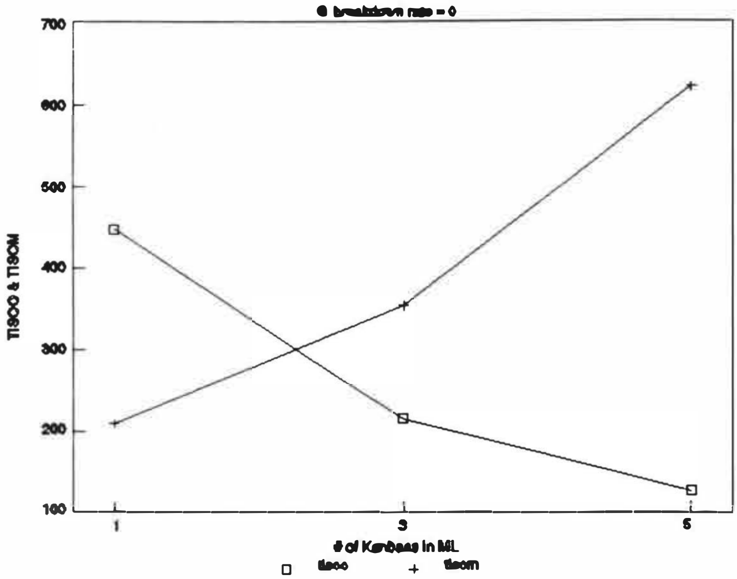


Figure e: Comparing Material lead time and Production lead time as number of Kanbans varies

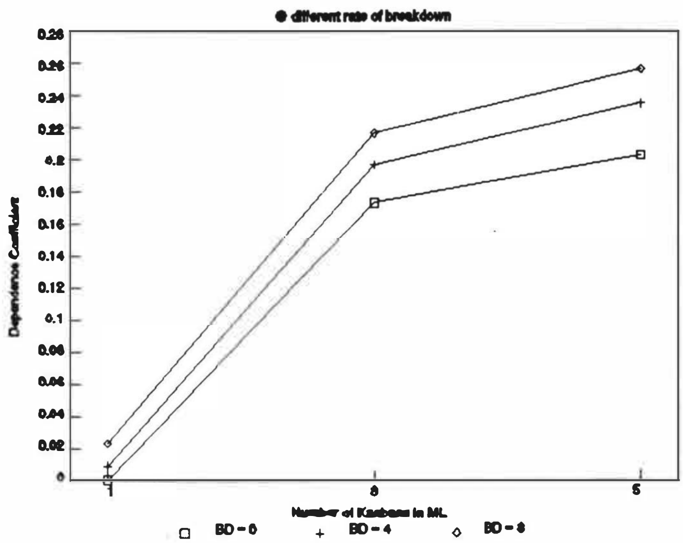


Figure f: Effect of number of Kanbans on Dependence Coefficient

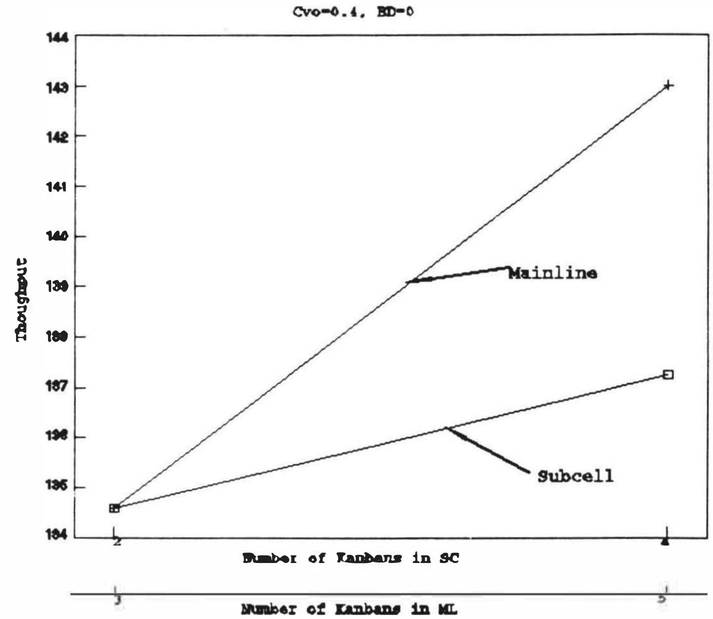


Figure g : Effect on throughput under varying Karban allocation strategies

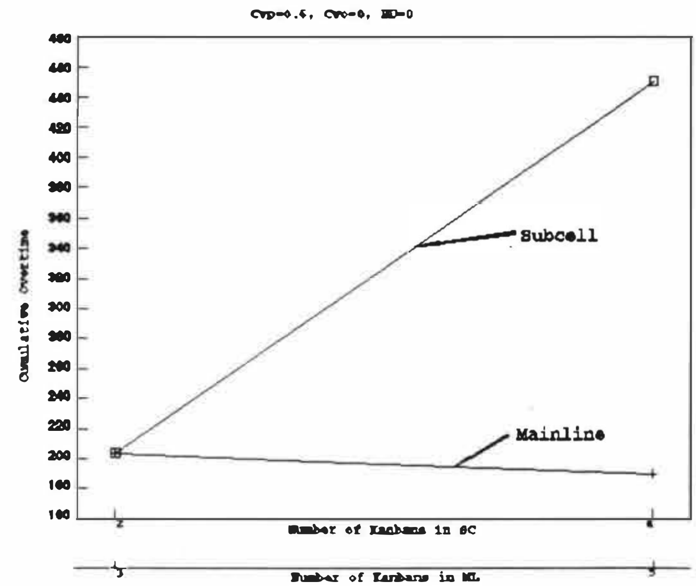


Figure h: Effect on Cumulative Overtime under varying Kanban allocation strategies

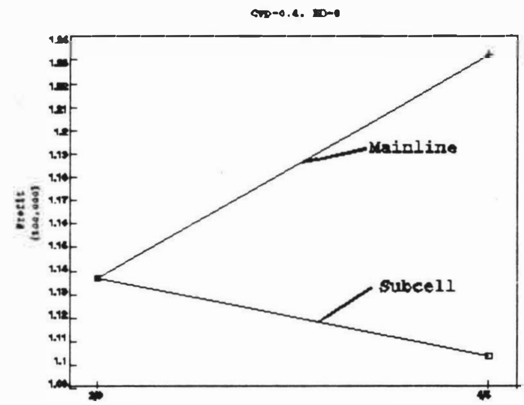


Figure i: Effect on Profit under vaYing Kanbans allocation strategies

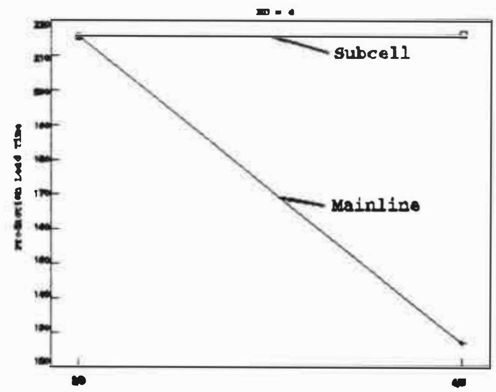


Figure j: Effect on production lead time under varying Kanbans allocation strategies

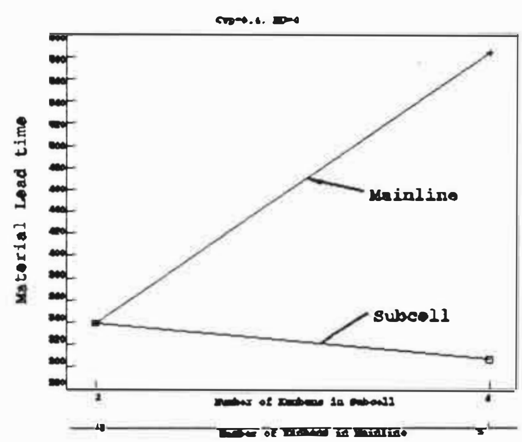


Figure k: Effect on Material Lead time under varying Kanbans allocation strategies

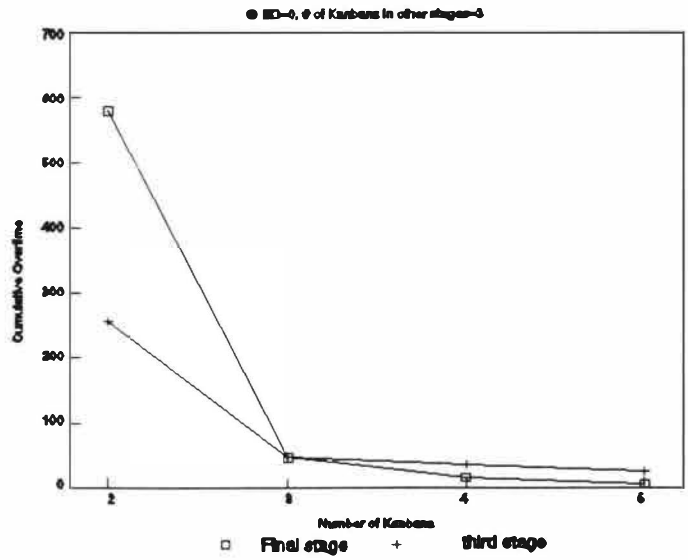


Figure l: Effect of varying Kanbans in third and final stage on cumulative overtime

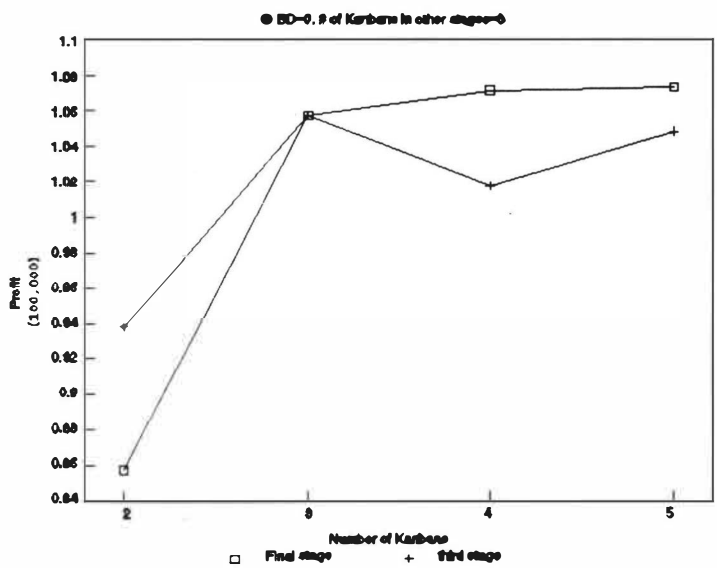


Figure m: Effect of varying Kanbans in third and final stage on profit

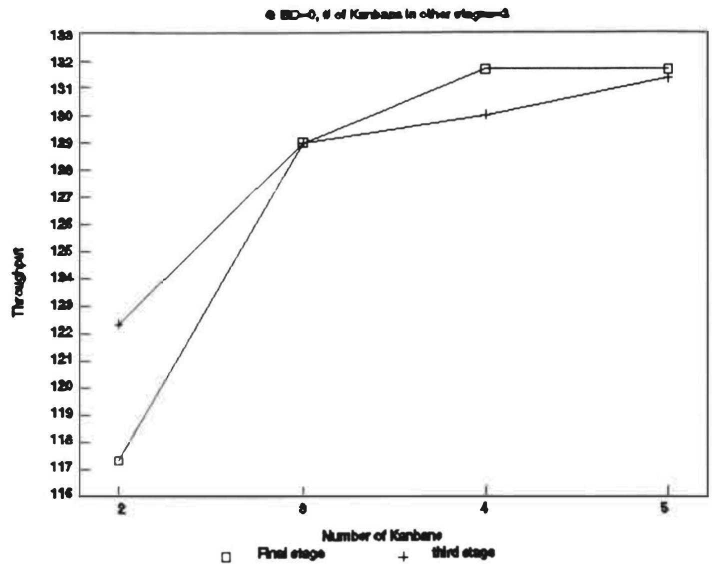
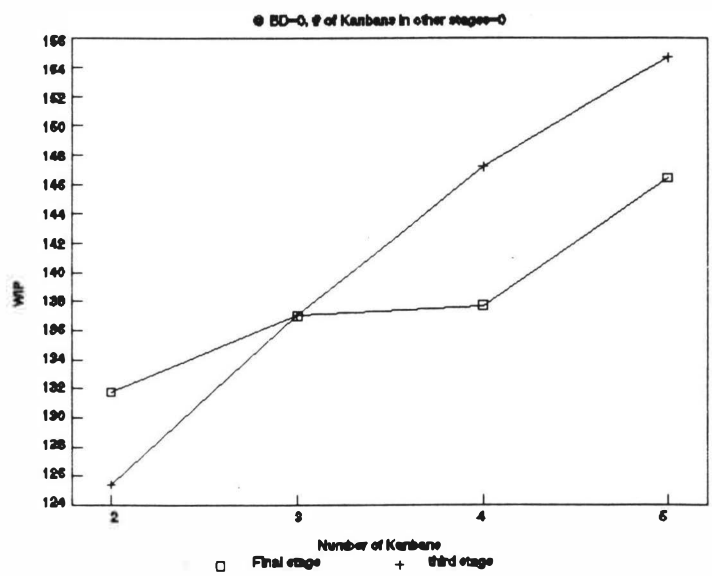


Figure n: Effect of changing Kanbans number at fourth and third stages on throughput



Figureo: Effect of changing Kanbans number at third and fourth stages on Work-In-Process

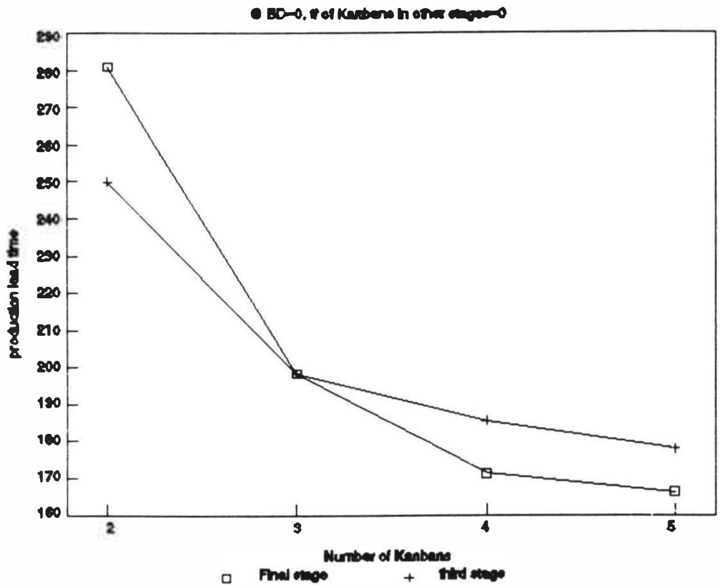


Figure p: Effect of varying Kanbans at fourth and third stage on production lead time

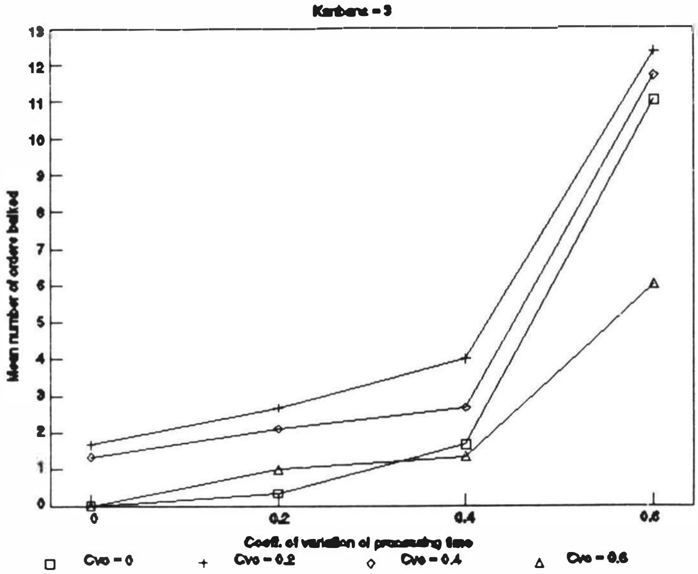


Figure q : Effect of variation on mean number of orders balked

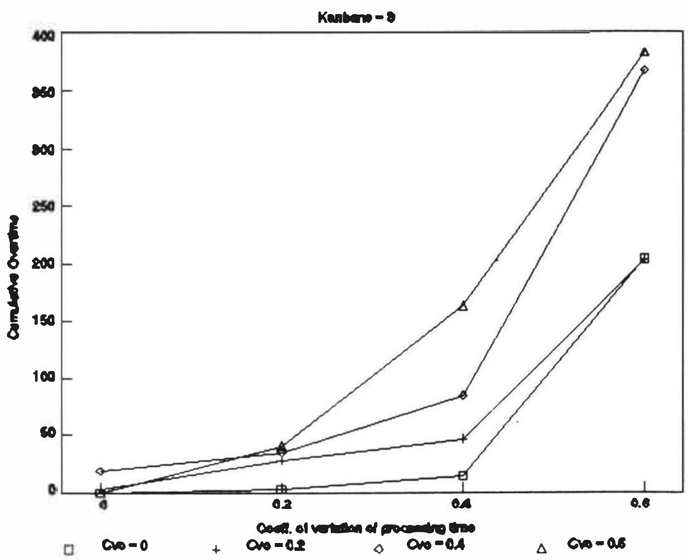


Figure r : Effect of variation on Cumulative overtime

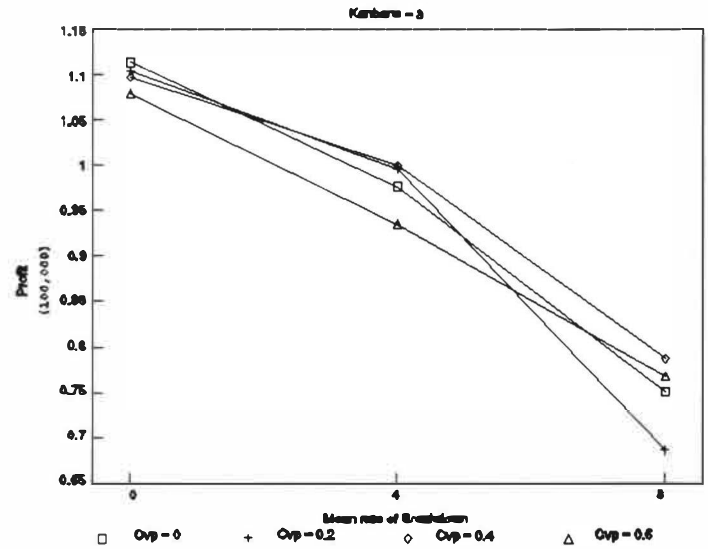


Figure s: Effect of breakdown rate on the profit at varying processing time variability

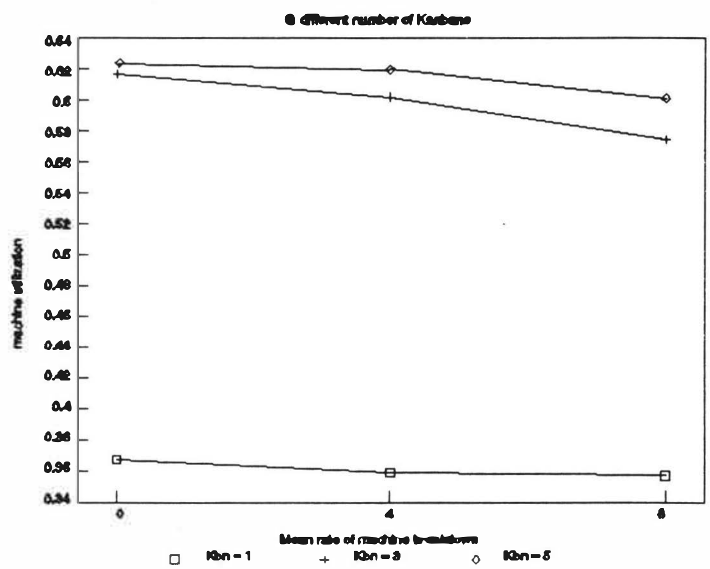


Figure t: Machine utilization as a function of machine breakdown

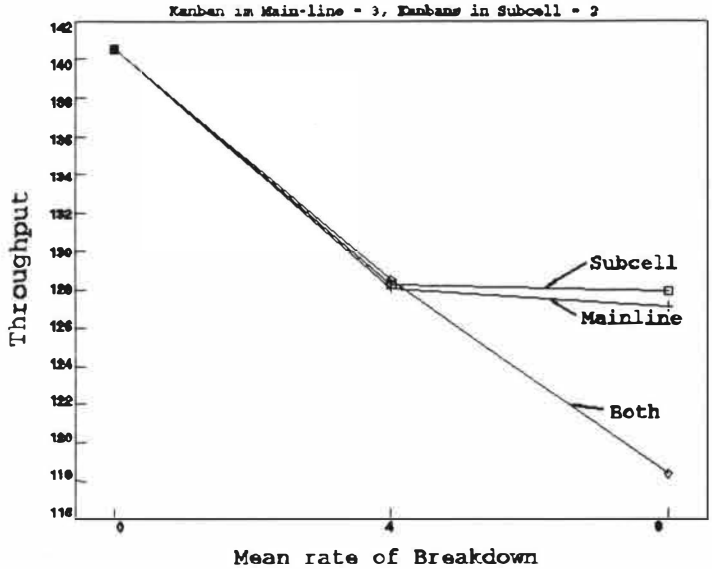


Figure u: Comparing throughput for different breakdown scenarios

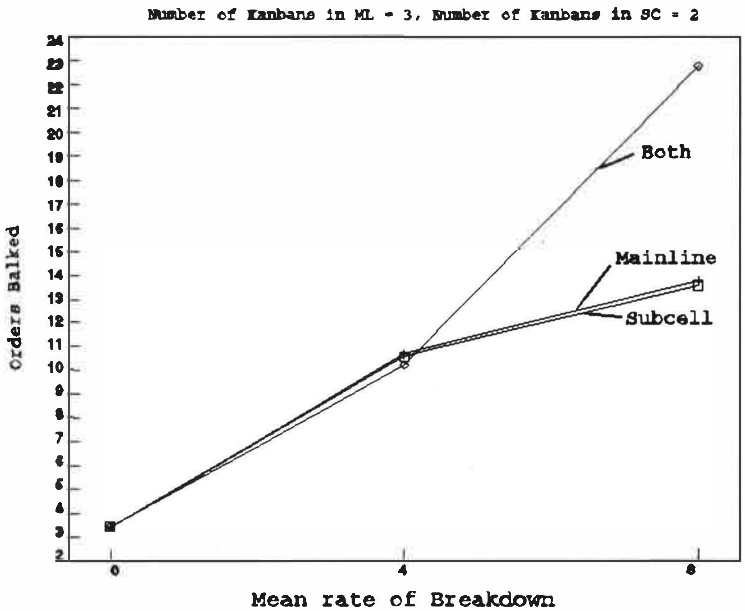


Figure v: Effect on number of order balked under different Breakdown scenarios

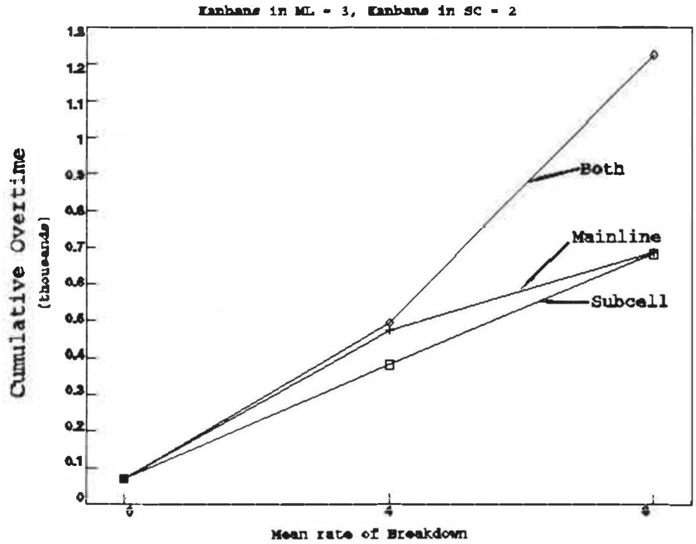


Figure w: Effect on Cumulative overtime under different Breakdown scenarios

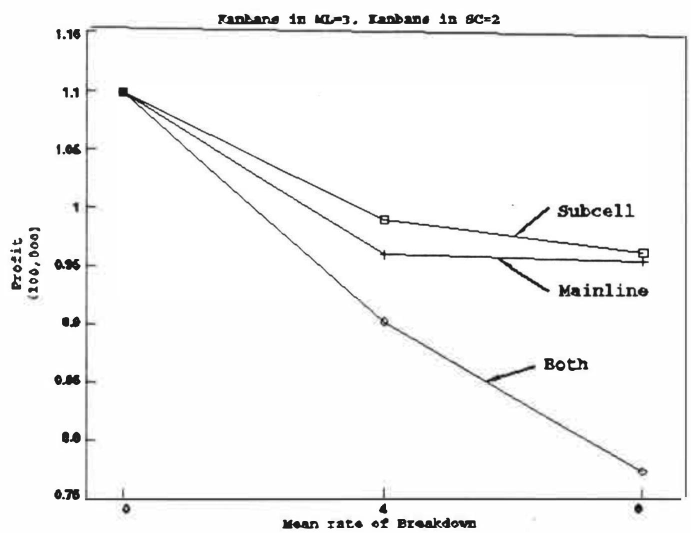


Figure x: Effect on Profit under different breakdown scenarios

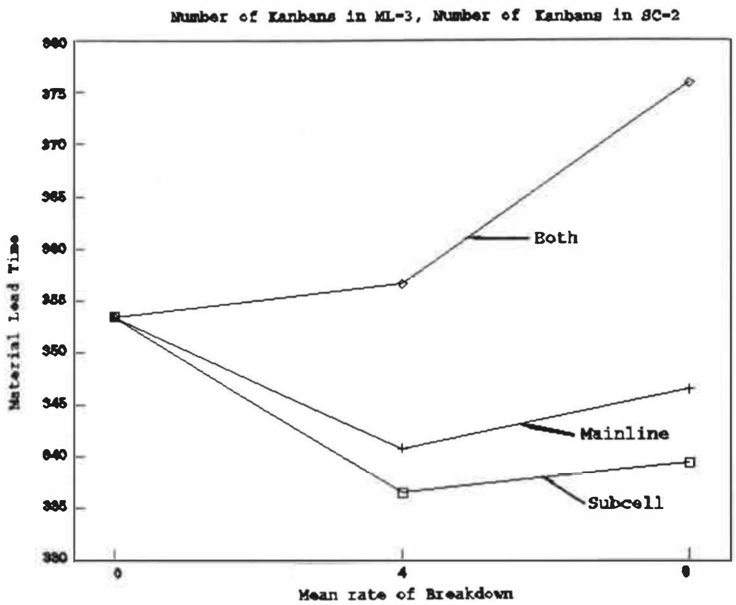


Figure y: Effect on Material lead time under different breakdown scenarios

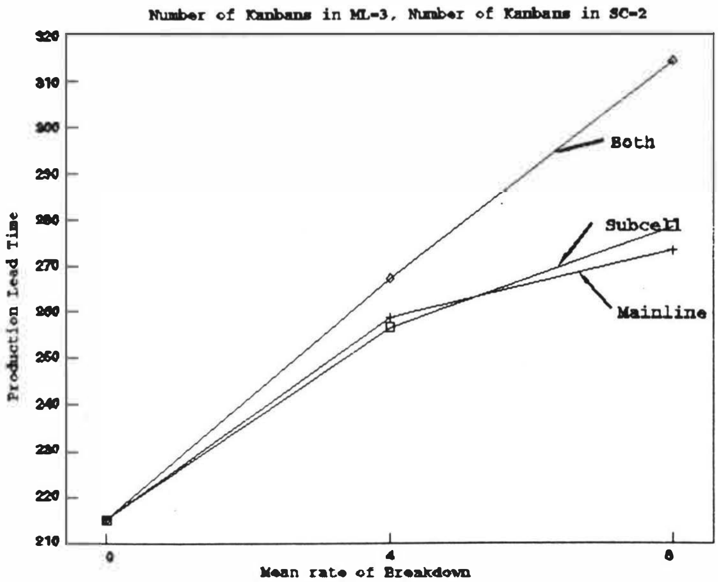


Figure z: Effect on production lead time under different breakdown scenarios

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